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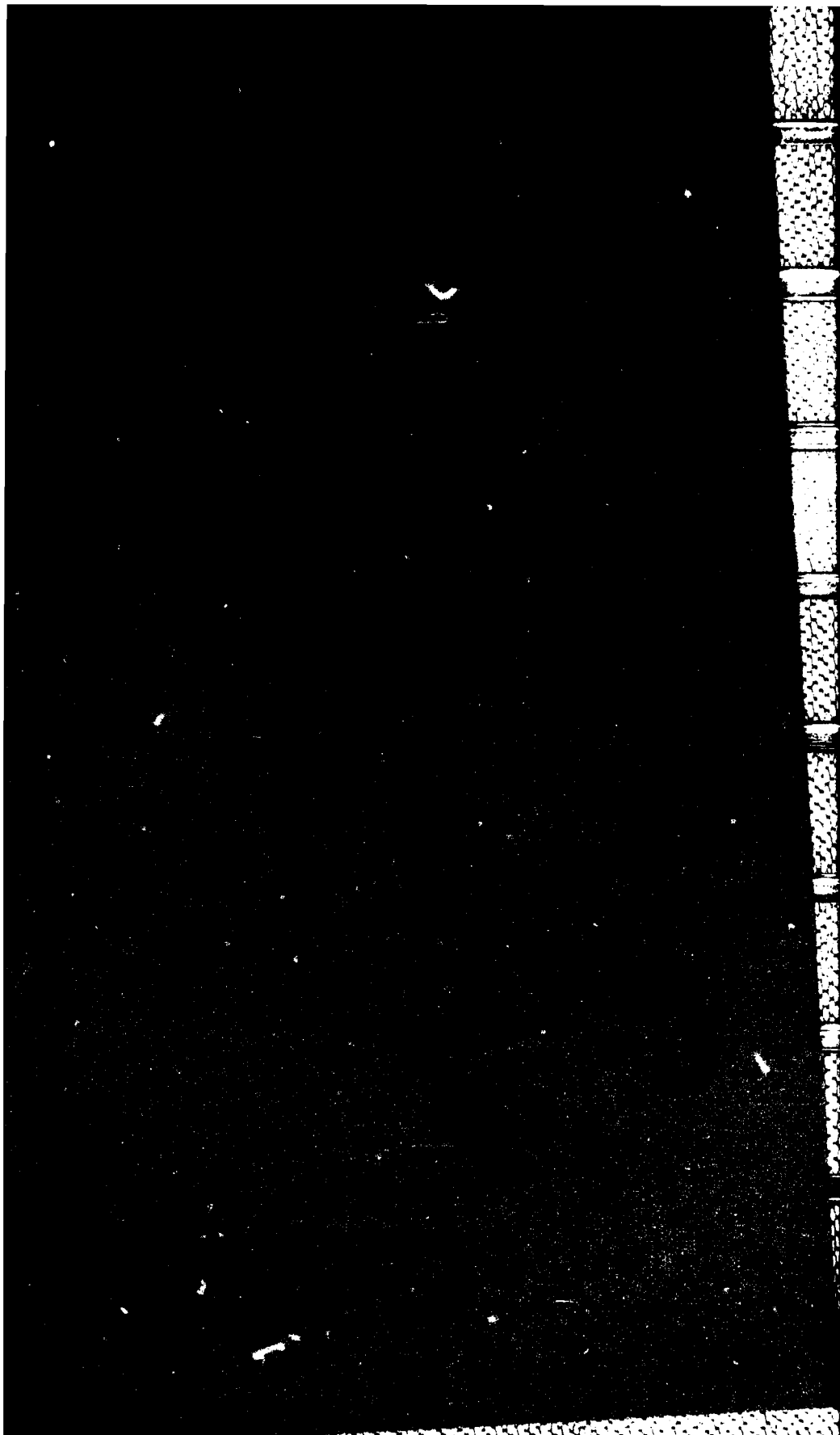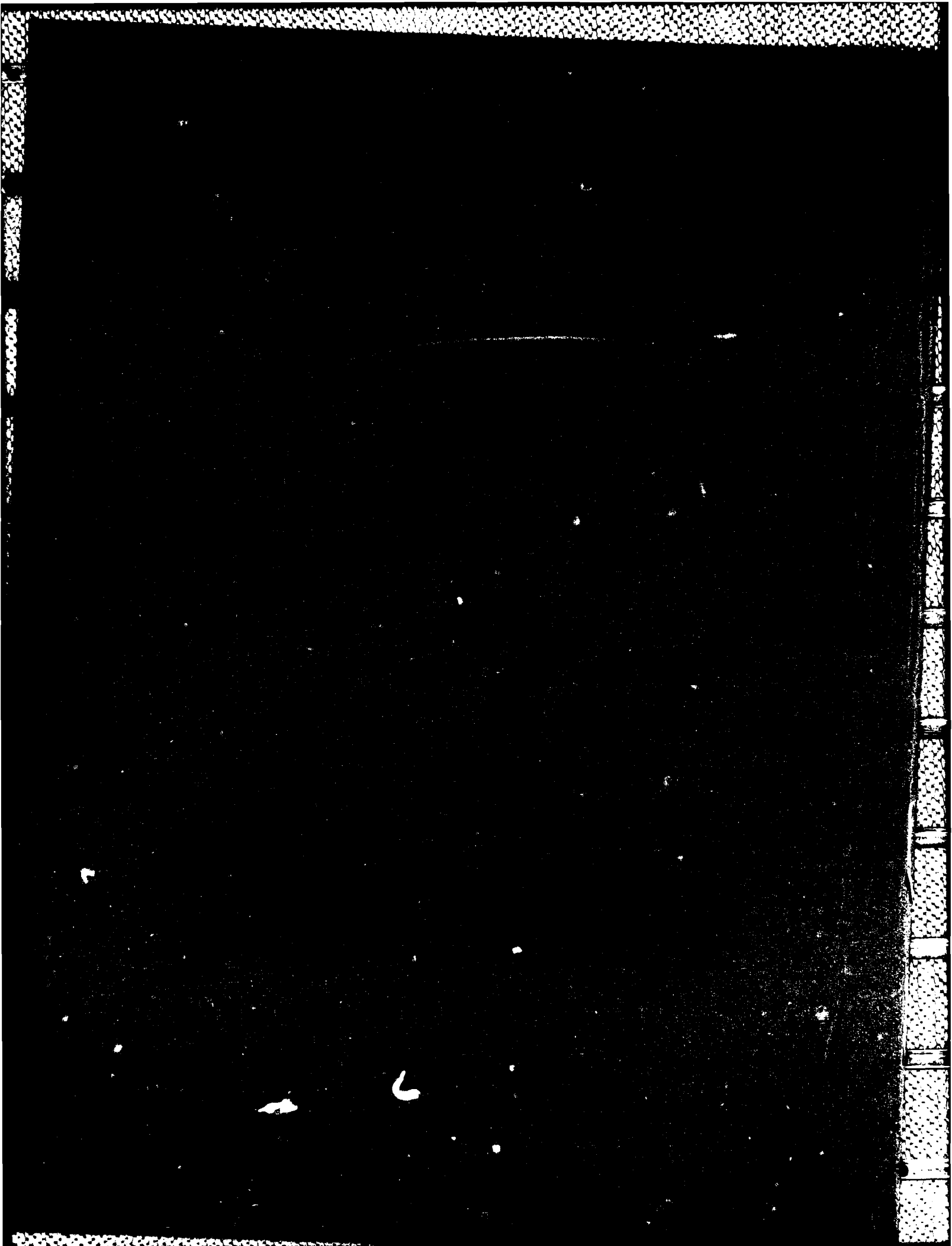| REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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Aviation and engine component repair requirements make up over half of the projected wartime depot-level maintenance workload. Organic (service-owned) ability to support this workload is particularly limited; at present, nearly half of the Navy's depot-level component repair is performed in contractor or other service facilities. Before major investments are made in the facilities and equipment needed to accomplish these repairs, it will be necessary to determine the appropriate mix of organic and contractor repair sources. This Note addresses the economic and operational implications of alternative source-of-repair decisions. Based on analyses of the distribution of projected wartime demands, technical data limitations, the structure of the repair industry, the operational payoff of facilities characterized by broad scope of repair, and airline industry practices, it postulates a strategy for providing depot-level component support that can be used to specify the appropriate source of repair at different points in the weapon system and subsystem life cycle. Keywords:

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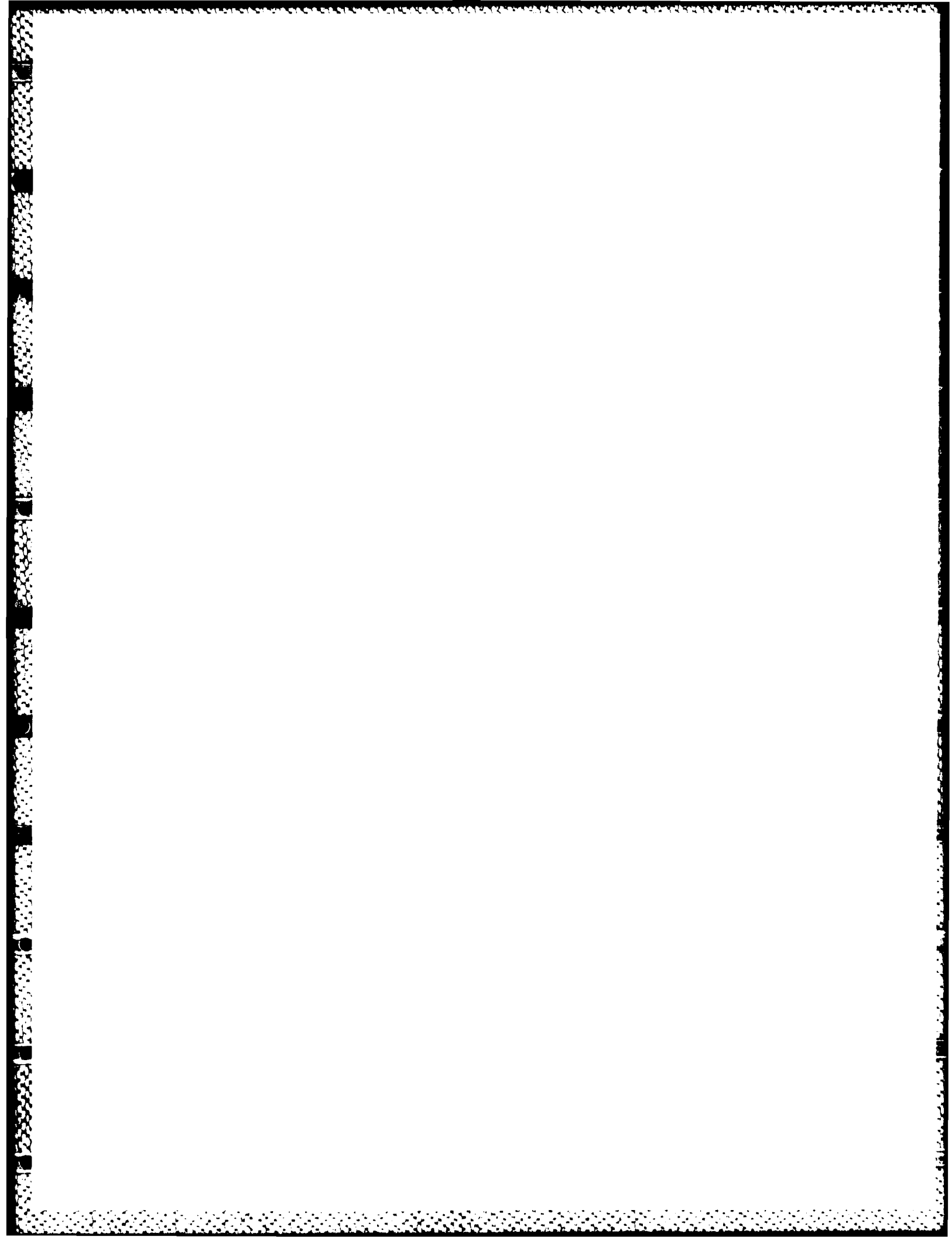
L. B. Embry, N. Y. Moore,
J. Cave, F. LaBrune

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Rand
1700 MAIN STREET
P O BOX 2138
SANTA MONICA CA 90406-2138

PREFACE

The U.S. Navy recently completed an analysis of wartime depot-level support requirements and capabilities. This analysis revealed major deficiencies in the ability of organic (service-owned) facilities to support the front-line aircraft currently deployed in the fleet. Accordingly, the service is about to embark on a major depot modernization program that will enhance organic support capabilities.

Aviation and engine component repair requirements make up over half of the projected wartime depot-level maintenance workload. Organic ability to support this workload is particularly limited; at present, nearly half of the Navy's depot-level component repair is performed in contractor or other service facilities. Before major investments are made in the facilities and equipment needed to accomplish these repairs, it will be necessary to determine the appropriate mix of organic and contractor repair sources.

This Note addresses the economic and operational implications of alternative source-of-repair decisions. Based on analyses of the distribution of projected wartime demands, technical data limitations, the structure of the repair industry, the operational payoff of facilities characterized by broad scope of repair, and airline industry practices, it postulates a strategy for providing depot-level component support that can be used to specify the appropriate source of repair at different points in the weapon system and subsystem life cycle.

The work described in the Note was supported by the Naval Aviation Logistics Center under Contract N00014-83-C-0100. It should be of interest to program and logistics planners concerned with establishing the mix of organic and contractor depot-level maintenance capability in the services.

SUMMARY

It is government policy to rely on the private sector to supply the goods and services needed to perform government functions unless there is some compelling reason to maintain "organic," or in-house, capability. The "national defense" exception to this policy is usually cited as the rationale for the services' maintaining their own large organic aeronautical depot maintenance complexes.

The services prefer to use organic maintenance facilities because they are:

- Easier to control;
- Perceived to be more flexible and responsive, and less expensive, than contractors;
- Reliable providers of the residual capacity needed to expand from peacetime to wartime production.

Navy policy is to use organic facilities to support the front-line weapon systems deployed in the fleet. Although organic capability does exist for airframe and engine work, many of the repairable components needed to support modern aircraft are currently repaired on contract. Component workloads will constitute over half of total repair capacity requirements in wartime.

Navy organic repair capability is not available for many high-technology components, because weapon acquisition programs have not funded procurement of the specialized resources needed. The service recently analyzed wartime repair capabilities and requirements and is now developing a depot modernization program to redress deficiencies identified in the current posture of the Naval Air Rework Facilities.

Component source-of-repair decisions are an important input to this modernization program. Major investments in specialized repair facilities and equipment will be necessary if the Navy is to change significantly the current mix of contractor and organic repair capability. This Note outlines the issues relevant to the workload

"reposturing" effort and postulates a strategy for providing repair capability across the life cycle of a weapon system.

SOURCE-OF-REPAIR DECISION CRITERIA

The Navy's spares support system can be visualized as a network of interconnected--hence interdependent--pools of stockage and maintenance (production) resources. Different echelons of the system are connected by a transportation system that moves components Beyond Capability of Maintenance at the intermediate level to the depot, and replacement components from wholesale to retail supply stockage points.

Depot repair is only one source of the components needed to sustain operational flying programs. The importance of its contribution is determined by:

- Projected flying programs;
- Intermediate-level maintenance performance;
- Logistics delays, including those encountered in depot-level repair;
- Stockage availability.

Significant opportunities exist for tradeoffs among resource categories within this integrated system. Since repair and transportation are inherently flexible, but stock can be used only to satisfy specific types of demands, there are many advantages to increasing reliance on the more flexible resources. This need for system flexibility--for "coupling" the logistics system to operational force requirements--is accentuated by the difficulty of accurately forecasting component demand, particularly for wartime.

The performance of other elements of the system affects the role of depot maintenance in providing operational logistics support. Source-of-repair decisions should consider this role, as well as a number of other interrelated factors. These include:

- The likely impact of component shortages on (peacetime and wartime) aircraft availability;

- Expected repair volumes in both peacetime and wartime;
- Variability in component demand;
- Component and repair process technology;
- Available sources of repair;
- Historical performance of different sources in meeting repair requirements;
- Relative costs of alternative sources;
- The rate of change in subsystem design.

One extremely important characteristic of most components is their low expected peacetime and wartime depot-level demand. Low repair volumes make it very difficult for any repair facility to provide repair resources efficiently and responsively. This is the primary rationale for establishing facilities that have broad "scope of repair," i.e., that can share common resources across a wide range of items. If the transportation and depot scheduling systems are responsive, this ability to share resources can have both operational and economic benefits.

At present there are no contractor operations with broad scope of repair; repair contracts are usually negotiated with the subsystem manufacturer. Contractors do, however, share resources, usually between production and repair. It is not clear whether current contractors have the surge capability needed to support mcbilization, or whether any available surge capacity would be used to expand production (as opposed to repair) upon mobilization. However, it does appear that they are less able than organic facilities to reallocate resources in response to changing operational priorities.

Low demand levels provide one explanation for the lack of firms specializing in component repair, particularly for high-technology components. Other reasons involve the implied information and capital investment requirements. Specialized knowledge is needed to perform most repairs, as are significant investments. Such investments are needed not only for relatively high-technology components, which constitute nearly half the inventory, but even for many lower-technology items. In short, demand uncertainty, low demand volume, technical data limitations, and capital requirements combine to create an extremely thin market for repair services.

THE COMPONENT REPAIR MARKET

At present, the market for component repair services shares one key characteristic with that for weapon systems. Both markets have one monopsonist buyer--the government--dealing with a monopolist supplier-- the manufacturer of the weapon system or equipment. For components maintained in organic facilities, the government's own internal source of supply effectively operates as a monopolist.

Manufacturers with repair contracts have a great deal of (supplier) bargaining power, which may be reflected in high prices. Some of the sources of this supplier power are:

- They are (usually) the sole source of supply for needed repairs;[1]
- Shortages can have serious operational implications;
- The manufacturer's sales agents/contract negotiators are more knowledgeable--and more focused--than government contracting officers;[2]
- Tapered integration[3] to provide competition is not a viable strategic option because of low repair volumes;
- "Switching costs"[4] are high, even for bringing the repair capability into an organic facility.

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[1]The government often does not own rights to the data that would be needed to solicit competitive bids, and investment requirements would discourage competition even if all the necessary data could be provided to potential bidders.

[2]Although this situation may also obtain in the case of prime equipment contracts, program offices are generally in a better position to negotiate than contract negotiators in a Navy supply activity, because the penalties associated with failing to agree on price and delivery schedule for a weapon system are much more severe than those involved with repair contracts.

[3]Tapered integration involves producing part of output internally and contracting for the balance. It has been used effectively by General Motors and can provide many of the benefits of producing the full quantity required internally while relieving the producer of the risks associated with volume fluctuations (Porter, 1980).

[4]Switching costs are the costs associated with changing suppliers (Porter, 1980).

In theory, since the government is the sole customer for most such repair services, it should have a great deal of buyer power to counterbalance that wielded by the supplier. Unfortunately, the factors that create supplier power also tend to dissipate buyer power.

The alternative to commercial repair also has its drawbacks. Organic facilities are normally the sole source for components assigned to them. Pricing for organic maintenance is based on historical performance (manhour requirements) and standard rates. Since there is no competitive price reference, any inefficiencies in past performance are perpetuated in the standards used to price future deliveries.

Thus the government buyer is dealing with a monopolist supplier whether maintenance is performed organically or on contract. While the motivations of different repair sources probably differ, there is reason to expect both contract and organic repair costs to be excessive. Nevertheless, previous studies suggest that the price of organic maintenance may be lower than that of equipment manufacturers.

A LIFE-CYCLE STRATEGY FOR PROVIDING DEPOT-LEVEL REPAIR

Airline companies face parallel problems in selecting repair sources. Large airlines perform virtually all of their own maintenance for reasons analogous to those the services cite to justify their preference for organic capability.

The three most common exceptions to the airlines' general policy of providing their own maintenance support occur when:

- New equipment enters the inventory;
- Old equipment is phasing out of the inventory;
- An individual airline's repair volume is too low to justify investment in organic capacity.[5]

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[5]One important difference between the airline and military source-selection problems is that many airlines use the same equipment so they can "pool" their repair demands either at the manufacturer's facility or within one of the airline companies. The services, in contrast, are normally the sole consumers of a particular type of repair service.

The Navy might reasonably follow the airlines' lead and adopt a life-cycle support strategy that involves:

- Reliance on the manufacturer for repair early in the life cycle:
    - Until designs stabilize;
    - Perhaps with incentives to increase reliability;
- Transitioning repair to a "controlled" source soon after a weapon is deployed with operational units;[6]
- Returning to contractor support as the technology ages and more potential repair sources become available.

There would obviously be exceptions to this general strategy. For example, workloads that are not expected to "surge" in wartime do not require surge capability.[7] Furthermore, the Navy's proposed solutions to existing problems with information (especially data rights) may increase opportunities for competitive procurement of repair services (Chief of Naval Material, 1984).

In the meantime, the logistics system should probably make extensive use of organic facilities because they are:

- An assured source of mobilization surge capability;
- Able to respond to a wide range of emergent requirements because of their broad scope of repair;
- Likely to have an economic advantage over contractors in view of severe limitations in the market for component repair services.

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[6]Currently, organic facilities best fit this definition. However, some contractual options, particularly Government-Owned, Contractor-Operated arrangements, may become viable once data rights issues are resolved.

[7]Such workloads may, however, contribute to the peacetime workload base needed to assure surge capability for other components.

All of these arguments, and particularly the last, are subject to further validation. Additional research is needed to: (1) specify actions that could enhance "coupling" between depot repair activities and the operational forces; and (2) determine whether incentives can be structured to encourage increased competition and contractor scope of repair.

For example, if barriers to information transfer were lowered and the government financed the capital investments contractors would need to enter the repair business, market structure and associated opportunities for competition would probably change. The issues of responsiveness and barriers to competition are addressed in the Navy's planned research agenda and its recent actions to address the data rights problem.

ACKNOWLEDGMENTS

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I. INTRODUCTION

The Navy employs three levels of maintenance to support its aircraft: organizational, intermediate, and depot. The organizational level performs routine aircraft maintenance and identifies and replaces defective components, including engines. Many of these components can be repaired and restored to service. Component repair is accomplished by either intermediate-level (I-level) repair activities, which are usually collocated with operational units, or within depot repair facilities. Depot facilities also perform heavy airframe and engine maintenance.

Although most component repairs are accomplished in I-level facilities located either afloat or ashore, depot-level component repair is big business. It accounts for over half of the $2 billion expended annually for depot-level repair services. More important, component repair is a critical element of the logistics capability needed to support both peacetime and wartime flying activity. The importance of this operational support role is apparent in the brief introduction to the aviation component support system provided below.

THE NAVAL AVIATION SPARES SUPPORT SYSTEM

Most aircraft components are "program related," i.e., the demand for replacement components is related to aircraft flying programs. Projected demand for component repair in peacetime and in wartime is thus a function of:

* Component demand rates (in demands per flying hour);[1]
* Projected flying programs;
* Stockage availability.

---

[1]Demand forecasts for program-related items usually assume a linear relationship between flying and component removals, e.g., doubling the level of flying activity doubles component demand. This assumption is tenuous for the reasons outlined in Donaldson and Sweetland (1968), Shurman (1970), Shaw (1982), Embry (1984), a d Kamins and Crawford (1984). However, demand for most components can probably be expected to increase at wartime activity levels.

Components that cannot be repaired at the I-level of repair are the primary source of depot workload, particularly in wartime.[2] Thus, estimates of the demand for depot-level repair must consider interactions among a number of logistics support resources and functions.

The Navy's spares support system can be visualized as a network of interconnected--hence interdependent--pools of stockage and maintenance (production) resources. Different echelons of the system are connected by a transportation system that moves components that are Beyond Capability of Maintenance (BCM) at the I-level to the depot, and replacement components from wholesale to retail supply stockage points.

This system is portrayed graphically in Fig. 1. Mission capability of the aircraft fleet will be degraded unless total stockage is adequate to cover the transportation and repair "pipelines" anticipated in wartime. The size of these pipelines is determined by the factors listed above.

Shortages of any component are likely to degrade aircraft availability. The impact of such shortages is a function of:

- The operational function of the specific component;
- The frequency and duration of shortages;
- The responsiveness of the system in providing replacements.

System interdependencies create opportunities to substitute different types of resources for each other, e.g., replacing stock with maintenance capability. Since repair and transportation are inherently more flexible than stockage, alternatives that would increase reliance on repair are preferable to those that increase inventory levels, particularly in view of the limitations of demand forecasts described in Sec. II. However, pipelines are currently quite long. The analysis in Sec. IV suggests that reducing these pipelines would increase system resiliency and decrease support costs.

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[2]Additional workloads are generated by airframe and engine maintenance performed at the depot.

Fig. 1 -- The Navy spares support system

THE DEPOT REPAIR-SOURCE-SELECTION PROBLEM

Depot-level repair is clearly an important element of the logistics support system. Repair-source-selection decisions should consider a number of factors, many of which have to do with the characteristics of the components requiring repair. They must also take account of the government's stated policy of relying on the private sector for essential goods and services unless there are compelling reasons for maintaining in-house capability (Office of Management and Budget, 1983a).[3]

Such decisions should consider:

- The likely impact of component shortages on (peacetime and wartime) aircraft availability;
- Expected repair volumes in both peacetime and wartime;
- Variability in component demand;

---

[3]Policy statements relevant to the source-selection issue are summarized in Appendix A.

- Component and repair process technology;
- Available sources of repair;
- Historical performance of different sources in meeting repair requirements;
- Relative costs of alternative sources;
- The rate of change in subsystem design;
- Ownership of the data rights needed to establish repair capability.

The last of these factors poses a particularly critical constraint on repair-source-selection decisions because the government has not procured data rights for many of the components used in the current aircraft inventory. Although the Navy usually does own the rights needed to establish organic repair capability, in many instances its rights to transfer data to other commercial repair sources are questionable.

The data rights issue is one of the main reasons for currently repairing most components either in organic facilities[4] or at the original manufacturer's. The service has announced a policy of acquiring unlimited data rights in future procurements (Chief of Naval Material, 1984). This policy change should expand source-selection options in the future. However, since data rights are an open issue for current components, and because they have limited the service's experience with contracting options, this Note focuses on the source-selection problem for the current system, i.e., where the range of options is constrained by past procurement decisions. Further research is needed to identify appropriate source-selection strategies once this obstacle to competitive contracting is removed.

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[4]Organic facilities are owned by the service and manned by Department of the Navy civilians.

DEPOT REPAIR ALTERNATIVES

Depot-level repair capability can be provided by organic facilities, other services, or contractors. Contracting options range from those in which the contractor provides all necessary facilities, equipment, manpower, and material for specific subsystems or types of components to those in which the contractor provides only manpower and management. The latter describes a Government-Owned, Contractor-Operated (GOCO) activity similar to those used extensively for ammunition production and maintenance.

The Navy recognizes that contractors have a role to play in depot-level maintenance. However, the service's source-selection "decision tree"[5] reflects Navy policy that organic facilities should have:

- The repair capabilities needed to support front-line weapon systems;

- Repair capacity to satisfy projected wartime workloads for these systems;

- Sufficient workload in peacetime to ensure that wartime capacity needs can be met.

Current Naval Air Rework Facilities (NARFs) do not satisfy these "requirements" (Kusmick, 1983). The majority of the component workload currently accomplished on contract supports front-line weapons, whereas much of that done in the NARFs is for older aircraft. This workload mix has evolved because organic capabilities have not been established for many of the newer technology components needed to support modern weapon systems.[6]

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[5]The Air Force pioneered development of a decision tree logic that can be used to specify the appropriate source of repair based on the characteristics of the item requiring maintenance and its relationship to combat mission demands.

[6]Many of these capability deficiencies result because the necessary capital investments, which often entail multi-million dollar expenditures for just test equipment, have not been funded by the weapon system acquisition programs. Acquisition managers have strong incentives to keep program cost within targets without reducing the number of weapon systems procured. System cost growth is accommodated frequently by reductions in allocations for support capability, including organic depot-level maintenance capability.

Component repair contracts usually cover a group of items associated with a particular subsystem. As was suggested above, they are generally negotiated with the contractor who produced the equipment.[7] Most of these contractors share equipment between production and repair, and many of them may use the same equipment to satisfy the needs of more than one service. Thus, estimates of their wartime repair capacity can be made only subject to assumptions concerning:

- Wartime production requirements;
- Other services' (production and repair) demands for available capacity;
- Contractor "surge" capability.

Furthermore, since each contractor is responsible for only a few components, current contracting practices yield a depot repair structure characterized by narrow scope of repair.[8] The implications of this structure are discussed further in the following three sections.

OUTLINE OF THE NOTE

The following section highlights some component characteristics that should affect the source-of-repair decision and presents the results of an analysis of component data for one front-line weapon system. Section III addresses the issue of wartime or "surge" capacity and highlights the sensitivity of time-phased surge workload estimates to distribution and repair performance. Section IV outlines some of the economic issues that bear upon the source-of-repair decision, including the implications of current repair industry structure.

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[7]Production contracts frequently make the equipment manufacturer the Design Control Agent (DCA) for the equipment. DCAs have specialized knowledge and equipment that uniquely qualify them for future repair contracts.

[8]Scope of repair is a technical economic term that refers to the range of items that can be repaired using similar resources. Broad scope of repair permits: (1) sharing similar resources across a range of components, which individually may generate small resource demands; and (2) allocation of available capacity to those components most likely to degrade aircraft availability if repair capacity is constrained.

Section V describes the airlines' approach to their source-of-repair selection problems. Section VI postulates a life-cycle logistics support strategy consistent with airline practice and the analyses presented earlier. Section VII concludes the Note by reviewing the major assumptions reflected in this work, which implicitly identify areas that require additional research.

II. THE AVIATION COMPONENT SUPPORT PROBLEM

The distribution of component demands is an important concern for both sizing maintenance facilities and estimating the effect of component shortages on aircraft availability in wartime. It is difficult to generalize across a broad range of components. However, some inferences can be drawn from an analysis of data on maintenance of peacetime repairable components. This section presents the results of such an analysis for the components used on one aircraft currently deployed in the fleet.[1]

This aircraft is well into the operational phase of its life cycle, so its design is relatively stable.[2] The analysis addresses most of the repair-source-selection factors listed in the Introduction; the others are addressed in subsequent sections.

COMPONENT DEMAND DISTRIBUTIONS

Any business, including an organic depot organization, must use demand forecasts to estimate the level of capital and manpower resources needed to satisfy demand. The aviation component repair forecasting problem is complicated because:[3]

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[1]Data sources are described in Moore, Embry, and Dey (1985).
Additional results of the data analysis are provided in Appendix A.

[2]All aircraft undergo modifications throughout the operational phase of their life cycles. These modification programs update the technology of critical aircraft subsystems, particularly avionics. The pace of change is particularly rapid during the early production phase of the life cycle. Section VII discusses the implications of the rate of change in subsystem technology for repair-source selection.

[3]These characteristics of the demand forecasting problem make it virtually impossible to apply Material Requirements Planning (MRP) techniques used widely in industry. The value of MRP methods for the production problem has also been questioned by both practitioners and academics. Sandman (1980) has found that they do not provide a good guide for scheduling, and Maxwell, Muckstadt, Thomas, and VanderEecken (1983) report that they have particularly severe limitations in the face of changing patterns of demand or supply availability.

- Removal rates for most parts are low;
- Considerably fewer than half of local removals require depot-level repair;[4]
- Material and labor requirements vary substantially with the condition of the component being reworked.

Figure 2 shows the I-level demand distribution for the components installed on the sample aircraft. Nearly all appear less than once per week at any I-level facility at normal peacetime flying rates.[5]

The subdivisions in the bars show the number of components having BCM rates within a particular range[6] for each of three levels of demand. The components most likely to create aircraft availability problems in the fleet are those with a combination of:

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[4]BCM rates obviously vary across components. A previous study (Lippiatt, Hillestad, Embry, and Schank, 1981) found that BCM rates for avionics components averaged about 20 percent for Weapon Replaceable Assemblies (WRAs) and 40 percent for Shop Replaceable Assemblies (SRAs). These results cannot be generalized to the full population of repairable aircraft components but do suggest that SRAs should constitute the majority of depot-level workload. Individual SRAs are particularly likely to have low expected demands at the depot level.

[5]Demand categories are defined for this and subsequent charts as follows:

Category	Demand Rate
Low	< 1/month
Medium	> 1/month, < 1/week
High	> 1/week

Additional data on component demand distributions are provided in Appendix A.

[6]These divisions are:

BCM Level	BCM Rate
Low	< 10%
Low-Medium	11-55%
Medium-High	56-99%
High	100%

Demand rate

Low

Medium

High

0　　200　　400　　600　　800　　1000

Number of components

☐ Low BCM   ▨ Low-med BCM
▩ Med high BCM   ■ 100% BCM
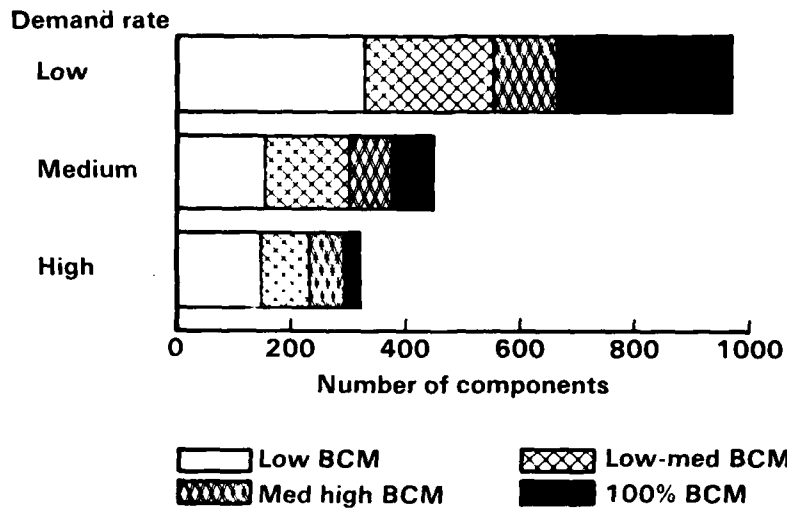
Fig. 2 -- Demand distribution at the I-level of repair

- Relatively high demand;
- High BCM rates.[7]

Figure 3 presents the expected demand distribution for these same components at the depot level. It indicates that the majority of components--over 80 percent--have expected demands at the depot level of less than one per month. If component demand is proportional to the flying program, maximum wartime depot demand rates for virtually all items are unlikely to exceed one per week.

Since most components require only a few hours to repair,[8] Figs. 2 and 3 suggest that depot-level manhour and test time requirements for

[7]Although failure of any component can degrade aircraft availability, shortages of those with small depot pipelines can be consolidated across aircraft by cannibalizing needed components from aircraft degraded by other parts shortages. Cannibalization cannot solve the spares shortage problem for components with large depot pipelines, nor can it accommodate large temporal "spikes" in demand if stockage levels are inadequate.

[8]Lippiatt, Embry, and Schank (1982) found that I-level repair times seldom exceed a few hours. Although depot repairs are often more complex, hands-on repair times also tend to be short at the depot level.

Demand rate

Low

Medium

High

```
0      200    400    600    800   1000   1200   1400
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Number of components
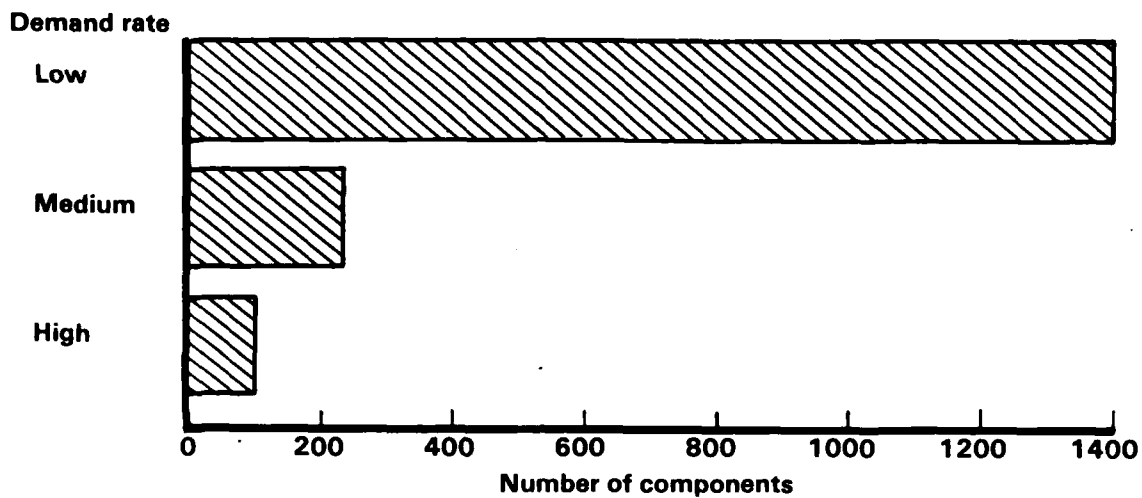
Fig. 3 -- Demand distribution at the depot level of repair

the majority of the population are extremely low. It would be
difficult--and costly--to provide repair resources to ensure that these
low volume components can be repaired when they are needed unless other
items can share these resources.[9] This is particularly true if rapid
repair turnaround is required.

Repair volumes tend not only to be low but also highly variable.
Figure 4 shows the range of total and BCM demands, for a group of
repairable components, experienced during two deployments of the USS
Nimitz. The demand rates shown in the figure have been normalized by
flying hours, so the variability about the mean should not exceed that
implied by the classical assumption that demand is generated by a simple
Poisson process.[10]

_____

[9]That is, unless the repair facility has at least some scope of
repair.

[10]This aggregate chart shows only the variability in total demand
for all components; similar charts for smaller groups of items would
exhibit even more dispersion in demand rates. Additional information on
the demand variability problem is provided in Crawford (1983) and Abell
(1985).
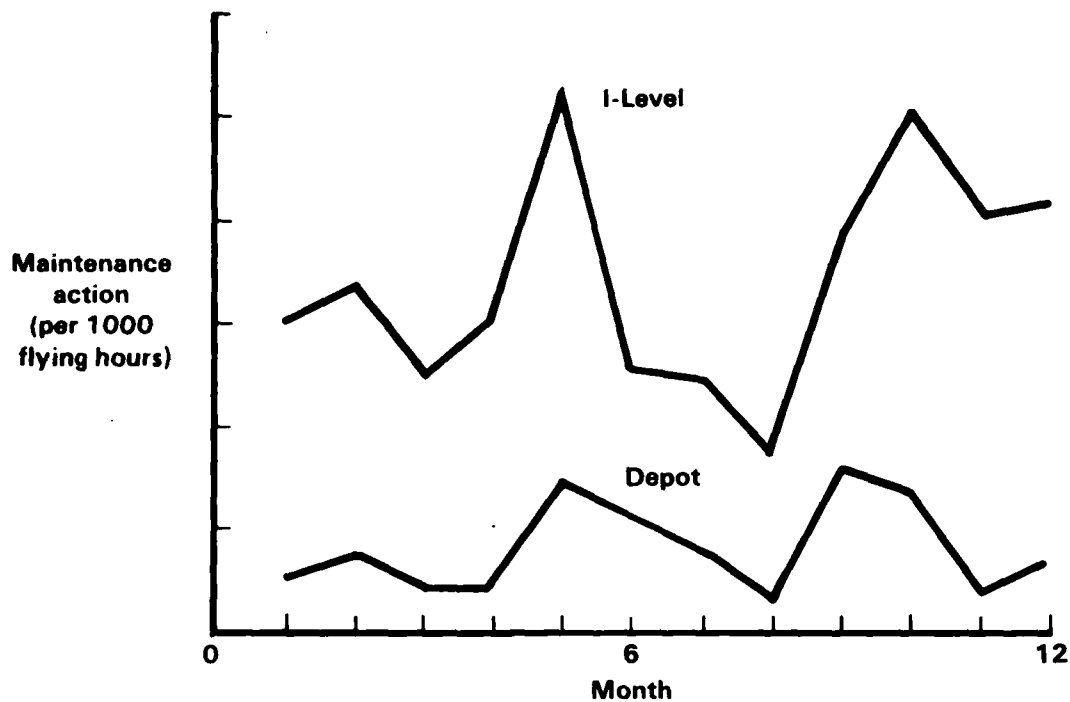
Fig. 4 -- Variation in demand rates during two Nimitz cruises

Demand variability clearly exceeds that implied by the Poisson assumption at the I-level but is within the expected range at the depot. This suggests that in peacetime the I-level absorbs much of the uncertainty associated with a variable demand stream. If I-level capacity constraints are encountered in wartime, however, the variability observed at the depot could increase significantly.[11]

Returning to the topic of "expected" demand, Fig. 5 shows the distribution of number of unique components and peacetime demand (in expected demands/week) by broad material category. In this figure, all repairable components on the aircraft have been assigned to one of four categories:

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[11]It should be noted that carriers appear to have substantial stock and repair capacity for most components. Thus they could continue to smooth variability in the depot pipeline unless parts shortages create implicit capacity constraints.
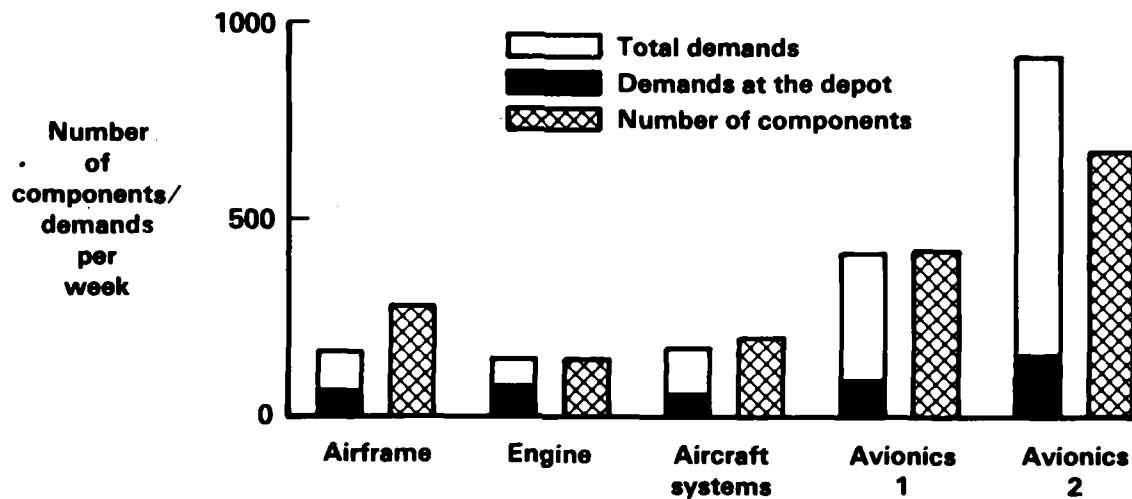
Fig. 5 -- Distribution of components and demand by material category

- Structural and aircraft systems;
- Propulsion;
- "Common" avionics;
- "Weapon" avionics.[12]

The "demand" bar shows both demand at the I-level and the subset of total demand that is sent to the depot. It indicates that there are major differences in I-level capability across different types of components. Figure 5 also reveals that only one material category-- the higher-technology avionics components--has average demands per week of more than one at the I-level. None average more than one per month at the depot.

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[12]This division of avionics components is somewhat arbitrary, but was made because repair processes for the second group tend to be more technologically sophisticated than those for the first group. The basis for the division was the component Work Unit Code (WUC). The first group contains WUCs from 51XXX to 69XXX, and the second those in the range 71XXX to 79XXX.

Depot-level facilities with broad scope of repair can program for a range of items, which makes it easier to estimate resource requirements. They can also take advantage of demand variability because average resource demands across a range of components will vary less than those for any individual item.[13] Scope of repair provides an additional advantage if total resource demands exceed available capacity, because scheduling rules that allocate available capacity to components most likely to affect aircraft availability can be used to "optimize" capacity use. Thus, scope of repair is desirable for both sizing and scheduling use of capacity.

COMPONENT AND REPAIR PROCESS TECHNOLOGY

Components with relatively high technology tend to have specialized test equipment, i.e., the repair process is itself technologically sophisticated.[14] Table 1 provides a cross-tabulation of component demand vs. repair process technology. The entries in the cells of the table indicate the number of components described by the row and column headings. The table reflects the assumptions that:

- Components used in structures and aircraft systems are characterized by relatively low-technology processes;
- Those in the category "Avionics 1" have more complex repair processes than those used in aircraft structures and systems, but less complex ones than those in the second group of avionics components;
- Engine and "Avionics 2" components will require more technologically sophisticated and expensive test equipment.[15]

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[13]That is, the variation relative to the mean demand is lower for a group of items than for any individual item.

[14]The repair process for many electronic components employs Automatic Test Equipment (ATE) and special test software for fault diagnosis. Engine repair requires balancing equipment and a test cell, and involves fitting components to very close tolerances.

[15]Since the aircraft considered has been deployed in the fleet for some time, few of its components are at the leading edge of technology. Nonetheless, subsequent discussion will refer to these items as "high-technology" components to simplify exposition.

Table 1

COMPONENT DEMAND AND LEVEL OF TECHNOLOGY

Depot Demand	Degree of Sophistication			
	Low	Medium	High	Total
Low	394	341	663	1398
Medium	64	63	105	232
High	25	17	54	96
Total	483	421	822	1726

Although there are exceptions to these generalizations concerning component technology,[16] two points stand out in this table:

• As was suggested earlier, almost 60 percent of the components have extremely low expected demands at the depot;

• Nearly half will require specialized, technologically sophisticated, and expensive test equipment.

The specialized investments required to support components in the right column of the table on average will be larger than for those in other columns. Almost half of the components fall in this category, yet fewer than 20 percent of them have expected depot demands in peacetime of more than one per week. Investments to support lower-technology items may also be substantial, but generally these investments will be for equipment that can be used to repair a wider range of components rather than for the more specialized equipment needed for high-technology repair.

The availability of repair sources also tends to decrease with increasing technology, as few suppliers have either actual or potential capability to repair items requiring technologically sophisticated

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[16]For example, the services plan to use high-technology composite materials extensively in new airframes.

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repair processes.[17] Current contracting methods, which usually favor
contracting with the system or subsystem manufacturer, do not exploit
the wider potential base of suppliers even for the lower-technology
items.

DEPOT REPAIR TIMES

Hands-on repair time is only a tiny fraction of the total time a
component spends in a maintenance facility (Lippiatt, Embry, and Schank,
1982). The length of the repair cycle, or the amount of time needed to
schedule and accomplish a repair, has an important effect on stockage
requirements and also influences the ability of the facility to respond
to critical requirements.

Figure 6 shows the distribution of depot repair times in organic
and contractor facilities for these components using "box plots" (Tukey,
1977).[18] Fifty percent of the observations are contained in the box
plotted for each group. The figure suggests that most repair times are
extremely long and that contractor repair times are even longer than
those in organic depots.

This aggregate comparison is affected by the current distribution
of depot workloads. Table 2 compares repair times for the subset of
items that have both commercial and organic repair times recorded in
Aviation Supply Office (ASO) files. The results of this analysis
reinforce the inferences drawn from Fig. 6.

It has already been suggested that most contractors share repair
and production resources. Hence it is not surprising that activities
dedicated to repair tend to have shorter repair times. However, repair
times in both contractor and organic facilities are excessive, and the
reasons for these long delays are not well understood. The following
section demonstrates that they affect projected wartime depot workloads
and indicates that they must be reduced considerably if depot repair is
to play an important wartime support role.

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[17]That is, a "competitive" market for repair services on components
that require sophisticated test equipment does not exist. The
government could, however, invest in data and equipment to increase
competition.

[18]The plotting technique encapsulates the distribution, showing the
median (plotted as ' * '), the "hinges" that define a box containing 50
percent of the observations, and the dispersion of the remaining data.

*Median
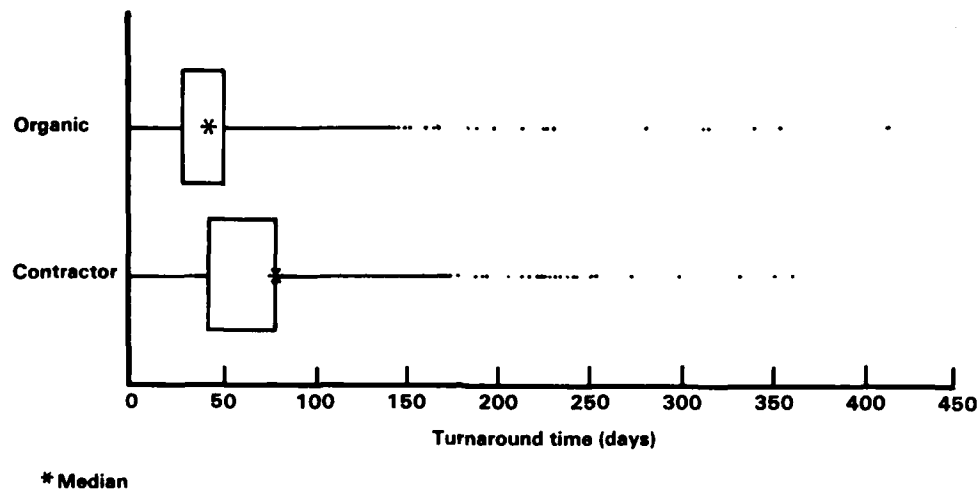
Fig. 6 -- Contractor vs. organic repair times

Table 2

REPAIR TIME COMPARISON FOR ITEMS REPAIRED
BY BOTH CONTRACTORS AND ORGANIC FACILITIES

Category	% of Items
Commercial < Organic	18
Commercial = Organic	5
Commercial > Organic	77
Commercial/Organic > 2	31
Commercial/Organic > 3	15

III. DEPOT "SURGE" CAPACITY REQUIREMENTS

The Introduction noted that the depot is part of an interdependent logistics system. The ability of depot-level repair to provide wartime operational support is influenced by:

- Distribution system performance;[1]
- Spares availability;
- Depot repair capacity;
- The range of items repaired at a single repair facility;
- Depot management philosophy and scheduling rules.

Distribution system performance affects depot support capability because it influences the timing of workload arrival. Stockage also plays an important role, because within certain limits stockage and repair can substitute for one another. Depot size, scope of repair, and management also affect the ability of a facility to provide responsive support.

This section illustrates the interdependence of distribution and depot support capability. The potential operational payoff of priority scheduling and scope of repair when depot repair requirements exceed available capacity is illustrated in Appendix C.

WARTIME DEPOT-LEVEL COMPONENT WORKLOAD ESTIMATES

Moore, Embry, and Dey (1985) describe a methodology that can be used to project wartime depot-level component repair workloads for a range of operational scenarios. Their prototype evaluation employed the same data that were described in the previous section. One important outcome of their work was a demonstration of the influence of

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[1]For purposes of the discussion in this Note, the distribution system is responsible for a component from the time a requisition is initiated until material is received, and from the time a BCM decision is made until the component is available for induction at the Designated Overhaul Point (DOP). Although these pipeline segments are often referred to as "transportation times," transportation delays account for only a fraction of total distribution time.

distribution system performance on expected wartime depot-level
workloads and spares stockage requirements.

The workload forecasting methodology distinguishes between two
alternative definitions of depot workload:

- Maximum workload, or the maximum depot induction rate, which is
  determined by the combination of operating-level BCM shipments
  and retrograde distribution delays;

- Minimum workload, or the minimum inductions required to support
  the projected flying program a repair time plus an Order and
  Ship Time (OST) away.

Figure 7 illustrates these concepts.
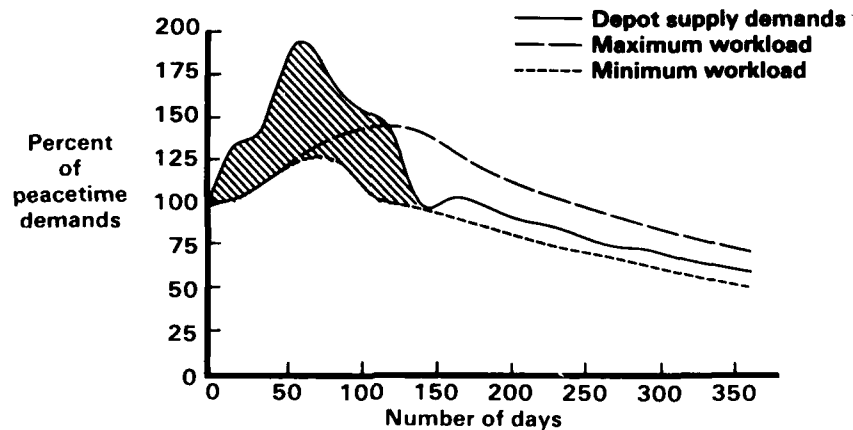
Fig. 7 -- Expected daily depot demands

The left-most curve in Fig. 7 represents daily expected component demands on supply for a particular operational scenario. The second curve is the maximum depot workload (induction rate) for an average retrograde delay of 60 days.[2] The final, or minimum workload, curve lies considerably below the maximum workload curve primarily because of anticipated reductions in the flying program.[3] The area below the demands on supply but above the minimum repair curve represents demands that must be satisfied from a serviceable stock inventory maintained in peacetime.

Facilities that are operated on a one-shift, forty-hour workweek in peacetime can surge to provide 150 to 160 percent of peacetime output for at least one to two months. Thus Fig. 7 suggests that depot facilities sized according to the rules established by Office of the Secretary of Defense (OSD) policy (OSD, 1982) can accommodate projected minimum depot workloads for this scenario. The results also suggest that a great deal of war reserve stockage is needed to support operations until repair production can meet operational requirements.

Figure 7's results are quite sensitive to assumptions concerning distribution system and depot performance. Figure 8 shows the change in minimum workloads that would result if: (1) average distribution times were halved; and (2) both depot repair and distribution times were halved.[4] The effect of both changes is to increase the minimum workload and reduce the implied stockage requirement.

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[2]A previous study (Johnson, 1981) found the average retrograde delay for aviation repairables to be 60 days. For purposes of this analysis, the delay consists of two components: (1) a fixed delay of 12 days, an optimistic estimate of the minimum retrograde delay; and (2) an exponential distribution with a mean of 48 days.

[3]As was suggested in Sec. II, I-level capacity shortfalls could result in increased wartime demands on the depot. The depot could also increase its contribution if peacetime maintenance backlogs provide a source of workload that could be inducted at the beginning of the scenario. Neither effect is reflected in this figure.

[4]Appendix D indicates that the structure of the depot repair system can influence distribution system delays.
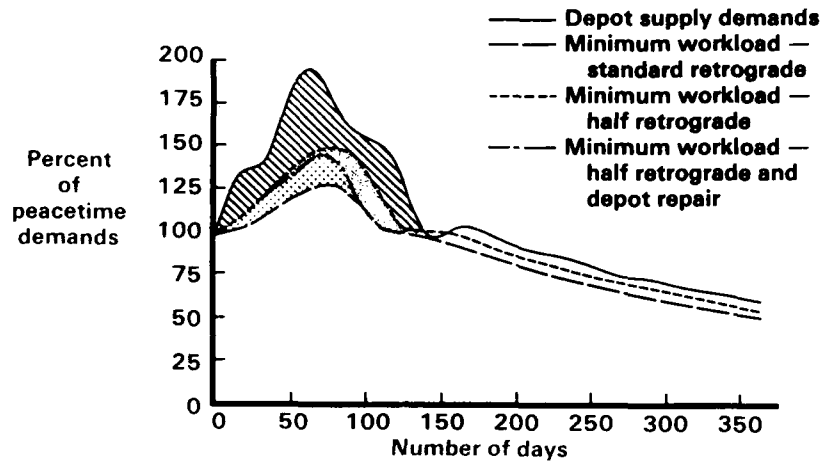
Fig. 8 -- Sensitivity of expected minimum daily depot demands
to logistics delays

Figure 7 also implies that even with these pipeline reductions,
which may prove difficult to achieve, the minimum workload is still less
than 1.6 times that experienced in peacetime. Although this result is
extremely sensitive to the assumptions used to develop workload
estimates, it suggests that depot capacity may not constrain operational
support capability.

"SURGE" DEMANDS AND DEPOT CAPACITY REQUIREMENTS

Nevertheless, surge requirements should be considered in selecting
sources of repair. Even if aggregate wartime repair requirements do not
exceed capacity, available repair capacity may be inadequate for
individual items. Such shortfalls are most likely to affect operations
if the number of items sharing similar resources in common facilities is
low, or when these are competing resource demands. Both of these
characteristics are more likely to describe a contract than an organic
repair facility.[5]

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[5]Resolution of data rights problems would permit establishment of
dedicated repair contractors with broad scope of repair.

Appendix C illustrates the potential payoffs of priority scheduling if aggregate capacity is insufficient to satisfy all demands for repair. In effect, any capacity shortfall can be allocated to those components least likely to affect aircraft availability given:

- A facility capable of repairing a range of items;
- The information needed to discriminate among critical and routine requirements;
- A scheduling algorithm that assigns resources to repair the most critical components.

In summary, the depot's role in fulfilling wartime support demands is determined by stockage availability, distribution system performance, and the depot's responsiveness. Repair-source-selection decisions influence both the level of surge capability available and the ability of the repair system to provide responsive support.

IV. ECONOMIC ASPECTS OF THE REPAIR-SOURCE-SELECTION PROBLEM

Ultimately the economic issues relevant to the problem of selecting component sources of repair can be reflected in the costs of different alternatives. Most of these costs, particularly those of inadequate support, are difficult to quantify. However, if all potential sources are equally capable of satisfying both peacetime and wartime demands, total repair costs will be influenced by:

- The industry and market structure of the repair business;
- Information transfer costs;
- Peacetime use of the capacity needed to respond to wartime demands;
- The costs and benefits of other actions implied by choice of a particular alternative, such as:
    - Changes in contract production costs if repair business is not available to absorb part of contractor overhead;
    - Methods used to maintain service familiarity with weapon technology if repairs are not accomplished in organic facilities.

Information costs, since they affect market structure, are particularly critical. As was noted in the Introduction, currently the data needed to foster competition in the repair business are not readily available. The Navy's recent actions to ensure "ownership" of data rights (Chief of Naval Material, 1984) are likely to lead to changes in the repair industry. However, since the effects of these changes cannot yet be observed, the following discussion addresses economic issues in the context of the current system.

COMPONENT CHARACTERISTICS, MARKET STRUCTURE, AND SOURCE OF REPAIR

The viability of the market for component repair services is influenced to an important extent by the nature of the support problem. Critical elements of this problem include:

- Item demand characteristics, including demand variability;
- A variety of information requirements, to include:
    - Technical data on the components;
    - Process descriptions for specific repairs;
    - Data on the relative importance of competing requirements for repair resources.

Section II noted that a small subset of the total population of items generate the bulk of both peacetime and projected wartime demands. The high demand components tend to be those with significant effects on wartime capability. Efficient repair of those with lower demand rates requires facilities that can share resources with production, or across a fairly wide range of similar components, to amortize capital costs.

Section II also suggested that depot-level repairables can be arrayed along a continuum of repair process technological sophistication. Few repair sources are either actually or potentially available for the items characterized by relatively high technology. In fact, at present there are usually only two potential sources of repair: the manufacturer and an organic facility. Although other sources could be qualified for the lower-technology items, usually they are also repaired by one of these two sources.

Finally, it is useful to categorize components by their "essentiality," i.e., their importance to the aircraft's mission capability. However, relatively few items can be classified as "nonessential" using the Navy's Subsystem Capability Impact Reporting matrix of subsystems and missions (Lippiatt, Hillestad, Embry, and Schank, 1982). The interdependence of components and subsystems that characterizes modern weapon designs, compounded by the interdependence of components within a subsystem, limits the range of items that can be excluded from the "essential," hence potentially "combat critical," list

of components. For example, it is extremely difficult to classify any particular component in a radar subsystem as "nonessential" for a particular mission because the radar is itself an integrated subsystem, and is also linked to other subsystems.

Although there are inevitably exceptions to generalizations, there tends to be a great deal of overlap among sets of components classified as high demand, relatively high technology, and essential.

Contracts should be easiest to establish for high demand components, because repair volumes are relatively stable. However, there are usually few potential repair sources, and shortages of these items could have a severe effect on operational capability. It is not clear that contracting with a sole source (monopolist) supplier will be "efficient," or that it would be desirable (for operational reasons), even if a contractor could produce at lower peacetime costs. Furthermore, an "efficient" peacetime repair process may lack both the flexibility and the surge capability needed to respond to wartime demands.

It may be more difficult to negotiate satisfactory repair contracts for low demand components, especially when contracts tend to cover the items used in a single subsystem rather than those sharing a repair technology. This is particularly true given an asymmetry in information between the "buyer" and potential "suppliers." Contractor representatives know a great deal more about the components and the repair process than the government representatives responsible for negotiating the contract. They are also likely to accommodate uncertainty in repair volume by charging prices that will cover slack time.

Changing contracting practices to group components based on similarities in repair resource requirements could increase contractors' scope of repair.[1] It is not clear how much changing the current practice of grouping components by subsystem would influence the availability of repair sources, but it could have important effects. Data concerning the current distribution of repair responsibilities (for the components that were considered in Sec. II) are presented in Table 3. The table suggests that current contractors have little scope of repair.

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[1]This presumes that the government owns rights to the data needed

Table 3

NUMBER OF COMPONENTS AND EXPECTED REPAIR VOLUMES
FOR CURRENT CONTRACT SOURCES

Components Assigned	Number of Contractors	Expected Units Repaired/week
1-5	26	0-6
6-10	4	2-8
11-25	3	3-13
> 25	2	8-12

Source: ASO data files.

Efforts to increase contractor scope of repair would also make it
necessary to address a number of information issues related to the
problem of source-of-repair selection. The availability of data
concerning not only the construction, but also the repair of specific
components[2] is at the root of the market problem. The efficiency of a
repair source increases with the level of such information available,
and the lack of relevant information creates market power for the
original manufacturer. Thus information costs may have a greater effect
on the viability of the repair market than the fixed costs of
capitalizing repair facilities, since the kind of information available
determines the extent to which repair facilities can work with a range
of components. An outline for a formal treatment of this issue is
provided in Appendix E.

by a contractor (other than the manufacturer) to perform repairs. The
Navy is taking action to ensure that data rights are procured in the
future (Chief of Naval Material, 1984), but does not own them for most
current equipment. Questions concerning data rights for current
equipment constitute a critical information problem.

[2]An important part of this information will not be found in the
manufacturer's technical data package, because it is based on the
experience of the people involved in performing component repairs. The
position of the government is weakened severely when it does not have
these data because it makes it more difficult both to establish organic
capability and to employ competition.

Finally, effective use of broad scope of repair requires an
effective system for communicating information concerning component
priorities. Organic facilities, which are linked into the service's
normal communication nets, may have a competitive advantage because of
their connection to "customer" organizations.[3]

In light of the above, the source-selection problem can be
formulated as a competitive strategy problem. Analyses of this problem
should consider:

- Purchasing strategy;
- Sources of supplier power;
- Strategies to negate supplier power;
- The rationale for vertical integration (Porter, 1980).

This analytic approach is illustrated in Appendix F. Two related issues
are addressed in Secs. VI and VII:

- *When* should organic capability be established, and how long
  should it be retained?
- What incentives exist or are needed to encourage cost control
  within the (monopolist) organic depot facility?

EMPIRICAL EVIDENCE CONCERNING THE CAPABILITIES AND COSTS OF REPAIR CONTRACTORS

Past studies have addressed the issues of:

- Contractor surge capability;
- Relative costs of different types of contractors;
- Comparative costs of contract and organic repair.

The most extensive study of contractor surge capability documented
in the literature was conducted by Booz-Allen Applied Research (1978).
Although it found that most contractors do have residual capacity that
could be used to expand repair output upon mobilization, it did not
address the effects that increased demands for new production would have
on this capacity, nor did it deal with potential competition among

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[3]See Appendix D.

services for available repair capacity. Interviews conducted with a number of firms during a major review of Navy ADM management found that firms typically do not consider these problems when questions are posed by a single service.[4]

Most studies of the relative costs of different types of contractors have focused on airframe and engine rather than component rework costs. One of the most important reasons that relative component repair costs have not been the subject of similar examinations is that there is usually only one source of repair for an individual component. The conclusions of the studies that have been conducted are generally consistent with those reported by Appleman, Seeberger, and Graham (1979), which found that:

- Prime contractors tend to be more expensive than organic alternatives;
- Sub-primes, or separate repair organizations split out within a prime, may be pri e competitive;
- Companies that specialize in repair may have lower repair costs than organic facilities.

One reason that prime contractors have high repair costs is that they usually must absorb part of corporate overhead, which includes engineering and management labor. In addition, they may use skilled personnel to perform tasks that could be done by less skilled people, and many of these contractors are located in areas with high unit labor costs.[5]

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[4] Conversation with John Maloof of the Navy's Aviation Intermediate Maintenance Support Office, August 1984. Mr. Maloof was a participant in the Navy ADM management study and discussed the surge capability issue with at least one major aircraft manufacturer.

[5] If the share of overhead absorbed by current repair contracts exceeds that attributable to the repair business, shifting the source of repair could result in apparent increases in some production costs. These cost increases may be offset by decreases in the costs paid by the Navy to maintain technical expertise in technologies that are not repaired in organic facilities.

Sub-prime manufacturers tend to have lower engineering burden rates and may also have lower labor rates. However, if their costs are approximately equivalent to those in organic facilities, it is not clear that the government should incur the additional problems of control that would accompany contracting with them for repair.

Repair specialists may have a cost advantage over government activities, but their capabilities are usually limited to repair of less technologically sophisticated items. Few (if any) repair specialists will be willing to make the capital investments needed to enter markets requiring sophisticated repair processes until data rights issues are resolved and contracting methods are changed. The alternative is for government to supply the capital and use contractors to provide labor, i.e., to establish GOCO activity.[6]

The Navy's studies of contract vs. organic repair costs have shown that organic facilities are very competitive for most components. Cost comparisons have generally compared contract and organic (industrial fund) prices (General Management Systems, 1982) or have otherwise deviated from the cost comparison guidelines established by OMB (1983b). However, in a number of cases organic repair has been estimated to be considerably less expensive than the contract alternative (Moore, 1983). Potential savings considerably exceed the minor differences that would result from using OMB's cost comparison guidelines.

In some cases where the contract alternative has proved to be less expensive, a primary reason for the contractor's cost advantage appears to be his use of ex-military people to perform repairs (Walter, 1980). In other words, the Navy has paid the contractor's training costs. This situation is most likely to obtain for older technologies.

Operational demands for depot support capability, coupled with market imperfections in the repair industry, suggest a need for organic repair capability in the current system.[7] However, different sources of repair may be appropriate for individual components at different stages of the weapon life cycle. A possible "life-cycle" source-selection strategy is outlined in Sec. VI.

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[6]The GOCO alternative is discussed further in Sec. VII.

[7]Again, resolution of data rights issues will affect the relative attractiveness of organic and contract repair.

THE COST COMPARISON ISSUE

This section has referred to previous comparative analyses of contract and organic costs, without presenting any detailed cost comparisons. Such comparisons are not included for a number of reasons, each of which is discussed further below:

- It is not always clear what work is being accomplished for a particular level of cost;
- Cost is an input measure, and no data are available to address the equally important quality issue;
- It is difficult to make meaningful cost comparisons across contractors, and even more difficult to compare contract and organic costs;
- Unit price data maintained for contracted repairs are unreliable;
- Relative costs have had little influence on evolution of the current mix of contract and organic repair.

The cost comparison problem is made particularly difficult by the fact that repair costs in different facilities do not necessarily reflect comparable repair activity. Frequently there are sizeable differences in the costs experienced by two organic facilities repairing the same component. Analyses of these differences have usually concluded that the "work package" performed in the two facilities differed significantly.

The work package should affect the quality of the product produced within a maintenance facility, but no data are available to compare at either the level of performance or the length of time to complete repairs by different repair sources. In the absence of such data, such comparisons are meaningless.

Additional complications are introduced by the differences in accounting practices used by the government and the private sector. For example, government accounting rules understate manpower costs because they do not reflect fully the accrual of retirement plan liabilities, and the "rates" charged by the industrial fund may include charges to

recoup past losses. On the other hand, commercial costs are affected by overhead allocation rules that may distort cost comparisons. The inexpensive diode for which the government recently paid $110 provides a particularly striking example of how allocation rules can distort cost data (Department of Defense, 1984).

The unit prices quoted in repair contracts reflect the contractor's original application of his cost allocation rules. They may also include services provided in addition to repair. However, contract negotiations usually focus on the expected dollar volume required for a range of components. Since these "bottom line" adjustments are not reallocated to individual components, and the original quotations may include services other than repair, comparisons of contractor and organic unit prices are likely to be distorted.

Finally, although cost is clearly an important factor to be considered in the repair-source-selection decision, it is not the only (and is usually not the governing) factor. Cost comparisons across contractors will assume increasing importance once data rights issues are resolved and competitive contracting becomes a viable option. This is not the situation that exists today.

The discussion of economic aspects of the repair-source-selection can be summarized as follows:

- A competitive market for component repair services does not now exist because of a combination of (1) component demand characteristics and (2) information transfer problems;
- Data concerning the relative costs of contract and organic repair are not necessarily comparable;
- Comparative analyses conducted in the past suggest that contract operations are unlikely to enjoy a cost advantage over organic facilities unless the contractors are repair specialists;
- Data rights issues and capital investment requirements constrain the service's ability to establish and support repair specialists;

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• Even if contractors could provide repair services at lower
costs than organic facilities, they would represent a viable
alternative only if they could also satisfy projected wartime
surge demands.

Resolution of the data rights issue will affect the relative
attractiveness of the contract repair alternative. However, the capital
requirements issue will still have to be addressed. Furthermore,
contracting methods should be changed to encourage repair specialists to
enter the market once data rights issues are resolved.

V. COMMERCIAL AIRLINE PRACTICE IN SELECTING
COMPONENT SOURCES OF REPAIR

The problems the major airlines face in supporting their fleets
parallel those that confront the services in peacetime. Because
aircraft and subsystem manufacturers frequently build on the knowledge
gained in military programs in their commercial designs, the airlines do
not usually have to face as much technological uncertainty as the
services when they accept delivery of a new aircraft. Furthermore,
airliners do not use most of the subsystems that increase the complexity
of military aircraft. Thus the "average" level of technological
sophistication is lower in airline than in military fleets.
Nonetheless, it is useful to review maintenance practices of the major
airlines to establish whether these practices, and the reasons for their
adoption, have application in the military.

AIRLINE "ORGANIC" MAINTENANCE CAPABILITIES

Large airline operators generally choose to perform nearly all of
their own maintenance. For example:

- Delta repairs 98 percent of the line items used to support its
  fleet;[1]
- United supports virtually all of its own repair requirements
  and also operates a major repair business to support other
  (usually smaller) operators;[2]

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[1]Conversation with O. H. Allen, General Manager, Material Planning
and Control, September 1984. Mr. Allen indicated that usually the only
reasons that Delta would not fix its own component were that: (1) the
component was proprietary and had to be returned to the manufacturer or
(2) repair volumes were too low to warrant investment in the needed
capital equipment. Since many airlines use the same component, they can
"share" capacity operated by a third party. The military is the only
user for most of its components so cannot usually exercise this option.

[2]Conversation with Tom Matteson, formerly the airline's Vice
President for Maintenance, August 1984. The smaller operators who are
customers for United's repair services would prefer to do their own
maintenance but lack the scale needed to economically justify
establishment of their own facilities.

- American also performs the majority of its own maintenance, and
  a former Vice President has suggested that its reasons for
  doing so are particularly applicable to the military (Hunt,
  1982; reproduced as Appendix G).

The reasons cited for these airlines' decisions to maintain
"organic" maintenance capability are very similar to those cited by the
services:

- Internal operations are easier to control than contractors;
- The size of their operations warrants the investment in
  specialized repair resources needed to maintain a wide range of
  components, which provides flexibility to deal with emergent
  requirements;
- Contract maintenance has been found to be more expensive than
  the organic alternative;
- The airlines are better able to maintain quality control within
  their own facilities;
- The costs of supply interruptions that could occur while
  contracts are renegotiated or during transition to a new repair
  source are prohibitive.

Since the costs to an airline of not having a needed component are
relatively easy to identify, airline operators are in a better position
to quantify the "control" argument than the services. The costs of a
shortage are considered too high to warrant reliance on an outside
source even though the airlines have relatively stable flying programs.[3]

Smaller airline operators may be at a competitive disadvantage
because they lack the scale needed to justify their own maintenance
operations. Although the equipment and training investments needed to
support different types of equipment vary, most maintenance processes
for modern aircraft are fairly capital (including human capital)

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[3]The services' need to both support peacetime flying and provide a
capability to "surge" repair output in wartime creates additional
demands for repair-source control.

intensive. Specialized facilities are needed for repair of structures, aircraft systems (e.g., hydraulics), and propulsion components, and many modern avionics systems require sophisticated test equipment.[4]

The costs of the required investment in specialized facilities, equipment, and training probably account for one primary difference between service and airline maintenance policy.[5] The airlines tend to favor a two-echelon maintenance structure over the three-echelon structure used in the military.

The airlines' usual procedure is to remove failed components at the flight line and evacuate them to a central point for repair. This promotes use of the available facilities and equipment and minimizes the total capital investment requirement.[6]

The tendency of both the airlines and the military to prefer their own maintenance capabilities supports hypotheses advanced in the organizational behavior literature. A potential shortage of replacement components poses a major uncertainty that can be limited by incorporating it within the organization (Thompson, 1967). Furthermore, if the alternative is to use contractors with a relatively narrow scope of repair, organic capabilities can enable both the military and the airlines to perform their missions more effectively.

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[4]Military avionics systems, since they tend to be even more technologically sophisticated, create even greater demands for investment in specialized diagnostic and repair equipment.

[5]Other major differences involve the airlines': (1) approach to defining maintenance requirements; (2) scheduled maintenance practices; and (3) control of distribution and repair pipelines. The services have begun efforts to apply some of the lessons learned by the airlines, particularly in their application of Reliability Centered Maintenance. This analytic approach to requirements definition is described in Nowlan and Heap (1978).

[6]There are both operational and economic reasons for the services' preference for extensive I-level capabilities. For example, the services must be prepared to conduct operations worldwide, and in locations where there are no established resupply channels. In addition, since failed components that cannot be repaired by I-level incur long pipeline delays (Lippiatt, Embry, and Schank, 1982), I-level investments may be economically viable. Shortening these pipelines could make a two-echelon structure more economically attractive for the military, but the current structure is likely to be retained for operational reasons.

EXCEPTIONS TO "NORMAL" SOURCING POLICY

Although the major airlines clearly prefer to operate their own
maintenance facilities, they do use contract maintenance in some cases.
These cases usually arise when:

* New equipment is initially introduced in the fleet;
* An older technology is being replaced;
* The airline's own repair volume is too low to justify
  investment in "organic" capacity.

United Airlines sometimes lets the equipment manufacturer pay the
maintenance "learning costs" for new technologies. This permits the
airline to delay investments in spare parts, etc., and to learn about
the repair process by observing the manufacturer's maintenance
experience.

Similarly, when older technologies are being phased out of the
active fleet, United sometimes develops commercial repair sources for
the dated technology. A specific (albeit dated) example involved the
airline's transfer of repair responsibility, as well as the equipment
needed for repair, for piston engines to a contractor during the
transition to a fleet powered by turbine engines.[7]

Finally, in some cases the combination of low projected demand
volumes and high specialized investment costs makes it economically
infeasible for a single airline to develop its own repair capability.
In these cases a group of airlines may designate one in the group as the
source of repair,[8] or they may continue to rely on the manufacturer for
repair services. Both of these options are made more attractive by the
fact that other operators can "share" investment costs. Since the
service is usually a monopsonist repair services buyer, ultimately it
must pay these costs either through establishing organic capability or
as part of the commercial repair price.

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[7]Conversation with Tom Matteson, *op. cit.*
[8]Such arrangements inevitably lead to conflicts in priorities among
the users, similar to those faced in interservice maintenance programs.

VI. A STRATEGY FOR PROVIDING DEPOT-LEVEL COMPONENT SUPPORT

Components differ, as do their potential impacts on operations and the range of possible sources of repair. However, some generalizations concerning where individual components should be repaired at different stages of the weapon life cycle are warranted. A reasonable strategy for providing depot-level component support, as long as data rights issues constrain the repair "market," would involve:

- Reliance on the manufacturer for repair early in the life cycle:
  - Until designs stabilize;
  - Perhaps with incentives to increase reliability;
- Transitioning repair to a "controlled" source soon after a weapon is deployed with operational units;
- Returning to contractor support, preferably with a repair specialist, as the technology ages, particularly if more repair sources become available.

THE EARLY PRODUCTION PHASE

The one fact concerning the configuration of a military aircraft that can be stated with certainty is that it will change.[1] Failures of the equipment originally installed, evolution of the threat, and the opportunities presented by technological advances will inevitably lead to redesign of major aircraft subsystems.

The rate of change in aircraft configuration is usually particularly rapid during the production phase of the life cycle. Since testing is frequently conducted concurrently with production (Rice, 1979), major deficiencies in design may not be detected until after the initial production units are deployed.[2] This instability in design makes it particularly difficult to develop efficient repair processes,

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[1]Structural components initially appear to present an exception to this general rule, but even they can undergo major changes. The wing slat modification installed on the F-4 long after the aircraft was deployed provides one obvious example of such change.

[2]Typical testing procedures also frequently fail to reveal the

even if the required changes are limited to test equipment software. Thus, using the manufacturer's facilities to accomplish repairs, at least until the design becomes relatively stable, may be preferable to establishing organic repair capability immediately.

Continuing changes in design will always require adaptation of fault diagnosis and repair procedures. The required amount of such adaptation can be limited by waiting to establish organic repair capability until the rate of change has slowed--perhaps one to two years after a system achieves its Initial Operational Capability.

THE OPERATIONAL PHASE

The Introduction noted that the only alternative to organic repair for most components installed on front-line aircraft is the original equipment manufacturer and highlighted the problems of creating other alternatives. Section II showed that demand rates for most components are very low and that those with high demand at the depot level are the ones most likely to affect aircraft availability. Section III suggested that priority repair can yield operational payoffs but that they can best be realized if:

- Test equipment is designed to repair a wide range of components;
- These components are assigned to a common repair source.

Finally, the analysis in Sec. IV suggested that contractor repair for high-technology items is likely to be more costly than the organic alternative unless the Navy can enhance competition in the repair business. All of these analyses motivate use of organic sources--the most readily available source characterized by broad scope of repair and ease of control--to repair components during the majority of a weapon system's operational life.[3]

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problems that will occur when the weapon is deployed in operational units (Cote and Birkler, 1979). Deficiencies in testing procedures exacerbate the problems resulting from concurrency in design and production.

[3]GOCO operations may be able to provide many of the advantages associated with the organic alternative if data rights issues are resolved and if resources can be made available to capitalize them.

The primary obstacle to establishment of organic capability is initial acquisition of the facilities and equipment needed to accomplish repairs. The incentives operative in the weapon system acquisition process often delay establishment of organic capability. Failure of past acquisition programs to fund procurement of essential resources has led to the current mix of repair capability and has created the need for a major depot modernization program within the Navy.

This program, however, will correct only past problems. Additional action is needed to ensure that current and future acquisition programs fund procurement of needed support resources.[4] Funding must also be allocated to keep equipment, manpower, and spares inventories in step with modification programs introduced in the field.

TECHNOLOGICAL AGING

Modification programs are used to maintain currency in system design, so some components even in older aircraft are technologically sophisticated. However, many subsystems are not modified to keep them current with the "state of the art" (Schwartz, Sheler, Cooper, and Pierce, 1968). Hence it is possible that new sources for some components may become available as a weapon ages, particularly if efforts are made to provide potential contractors with the capital equipment and technical data needed to accomplish repairs.

Civilian end-strength ceilings are a political reality, even though they are inconsistent with the philosophical basis for industrial funds.[5] As new items enter the inventory, the depot needs to develop a capability to repair them to:

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[4] Depot equipment deficiencies provide only one example of the underfunding of support capabilities in acquisition programs. Frequently, funding for initial spares acquisition, establishment of intermediate-level maintenance capability, and repair software and technical documentation is cut to ensure that programmed end-item quantities can be procured. Implementation of the Navy's new policy of acquiring unlimited data rights in new acquisition programs is likely to encounter similar obstacles.

[5] Industrial funds (IFs) were established to provide a financing mechanism for internal "businesses." One of the original concepts was that IF managers would be able to adjust workforce levels in response to changing workloads. Including IF activities within the civilian manpower ceilings deprives IF management of much of the flexibility that

- Maintain the service's level of technical knowledge;
- Keep the workforce trained to work with current levels of technology;
- Realize the benefits of the depot's broad scope of repair.

This may require finding new sources of repair for old items to enable important workloads to be accomplished within end-strength ceilings. Such sources should become more readily available as equipment ages.[6]

RELATIONSHIP TO INDUSTRY PRACTICE

The strategy outlined above is consistent with the airline practices outlined in the previous section. Although the airlines sometimes use different sources of repair at different stages of the aircraft life cycle, the military should not necessarily adopt a similar strategy. However, the motivations to do so in both cases are quite similar.

Other similarities between the problems faced by military maintenance managers and their counterparts in the airline industry probably warrant increased efforts by the military to learn from commercial experience. For example, airline depot flow times are considerably shorter than those observed in military systems. Military support capabilities would improve, and support costs could be reduced, if commercial maintenance scheduling rules and work-in-process inventory control practices were adopted by the military.

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originally justified creation of the funds. Although it appears that formal ceilings may be (temporarily) lifted, the sheer size of the organic maintenance workforce will continue to make it difficult for politicians to ignore.

[6] However, it should be noted that the Navy has found it difficult to identify commercial repair sources for many of the older items in the current inventory. GOCO facilities could be established by transferring equipment from an organic depot to a contractor if other sources are not available.

POSSIBLE EXCEPTIONS TO THE LIFE-CYCLE SUPPORT STRATEGY

Just as the airlines have exceptions to their normal source-of-repair policies, deviations from the proposed life-cycle support strategy may be appropriate in specific instances. In particular, contractor repair may appear to be preferable throughout the weapon life cycle if:

- Little need for surge ability in wartime is anticipated;
- Many sources could provide the required repair services;
- The service chooses not to establish organic capability because of:
  - High investment costs for specialized equipment that would be used infrequently;
  - Anticipated difficulties in hiring and retaining people with the skills needed to accomplish repairs;
  - Other reasons;
- Expected repair volumes are so large that a specialized repair facility is justified.

Most demand for low surge workloads is generated by the aircraft maintenance line. Wartime planning usually assumes that aircraft inductions will cease upon mobilization, and increased wartime flying programs should not result in increased demands. Wartime surge capability may not be required for such components,[7] but the workload may provide part of the base needed to ensure adequate surge capability for other components.

The other primary reasons that the government may choose not to establish organic capability relate to the costs of particular types of maintenance capability. For example, if multiple repair sources are available, as may be the case for both dated technologies and components that are similar to those used in the commercial sector, surge capability may be available in the industrial base and contract repair may be less expensive than the organic alternative.

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[7]Mobilization planning also assumes that efforts to complete the aircraft reworks in progress will be accelerated. This may generate some immediate, albeit short-lived, surge requirements.

Peacetime cost should not, however, be the only factor considered
in selecting sources of repair. Depot capabilities are maintained to
support both peacetime and wartime operations. If organic facilities
can be shown to be more responsive to operational requirements,
particularly in wartime, organic capability may be justified even if it
is costly. And if volume is sufficient to warrant establishment of a
dedicated repair facility, it could be split between two or more
sources--one of which might be organic--to realize the benefits of
competition. This is true not only for single component workloads but
for facilities with similar technical capabilities and broad scope of
repair.[8]

In short, repair-source-selection decisions must consider all of
the factors outlined in the Introduction. The general strategy outlined
above was based on consideration of these factors, but there are bound
to be exceptions. Decisions concerning such exceptions should be based
on similar analyses.

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[8]In other words, "tapered integration" in the repair business might
deal with specific repair processes rather than particular products (see
Appendix F). GOCO facilities are also an obvious alternative.

VII. CONCLUSIONS

Discussions of the alternatives for providing depot-level component repair often seem to focus on two extremes. The services prefer to accomplish repairs in organic facilities manned by wage board labor and financed by the industrial fund. The alternative usually addressed is contract support, where the "contractor" considered is usually the equipment manufacturer.

Organic facilities potentially can offer:

* Surge capability;

* Broad scope of repair;

* Sensitivity to operational force requirements.

The discussion in Sec. III indicated that the latter is currently more a potential than an actual organic advantage for providing wartime support.[1]

Although current contractors cannot assure any of these capabilities,[2] much of the argument for organic capability hinges on the assumption that viable commercial repair options cannot be generated for most components, i.e., that there is no viable "market" for component repair services. Some economists would challenge this conclusion, asserting that if the appropriate incentives were provided, additional firms would step forward to compete for a piece of this very large business, but Sec. IV indicated that information availability problems must be overcome before the incentives issue can be addressed.

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[1]Organic facilities do respond to emergent problems in peacetime. However, their ability to provide responsive support, particularly in wartime, is hampered by sluggish distribution system performance and excessive repair cycle times.

[2]Some contractors may have surge capability but it is not assured, because there are likely to be competing demands for limited resources in wartime. Current contracting methods, which focus on subsystems rather than repair processes, promote narrow scope of repair. Finally, although contractors may be sensitive to "customer" requirements, means to provide them with the necessary information to respond, particularly in wartime, are not well developed.

There are also several other potential alternatives:

- Interservice support, or "contracting" with another service;
- Contracting for repair of a range of similar components rather than just those used in a particular subsystem;
- Using "investment integration"[3] to provide the capital, and permitting private operators to compete for service contracts.

Interservice support is used to a limited degree to accomplish current depot workloads. Proposals to establish a single manager for Aeronautical Depot Maintenance carry this alternative to an extreme.[4] However, extensive use of interservice support would inevitably lead to serious conflicts among service priorities. Thus it is not clear that the potential benefits of "coupling" the depot to the operational forces could be realized in a system that makes extensive use of such interservice agreements.

The primary difficulty with changing contracting practices is likely to be a dearth of contractors interested in bidding on a range of components. A firm seeking to enter this business would have to confront:

- Natural barriers to entry in the market, including those of obtaining the specialized knowledge needed to perform repairs;
- The need to invest in specialized repair capacity that has no ready alternative use outside of the military repair business.

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[3]Investment integration is similar to vertical integration, but involves making only the required investments, leaving them to be operated by another organization (Hayes and Wheelwright, 1984). The GOCO alternative provides one example.

[4]The primary arguments for a single manager or increased use of interservice support involve potential cost savings, but it is not clear that increasing interservice support would reduce total logistics system costs.

It has been noted repeatedly that often the government does not own the data rights that would be needed to enable other firms to enter the repair market.[5] A related problem is that the information needed to group components with similar repair resource requirements is not readily available to government contracting officers. These factors provide one explanation for the lack of competitors for repair business, particularly for items based on relatively new technologies.

Another explanation concerns the investments required to enter the repair business. Although the capabilities of different contractors vary significantly, it is unlikely that many would be willing to make the capital and other investments needed to expand their scope of repair. Most contractors view equipment production, not repair, as their main line of business.[6]

The government could also use investment integration to put commercial operators in the repair business. The limited evidence that commercial operators organize to perform support functions more efficiently than the government suggests that further examination of this alternative is warranted (Paulson and Zimmer, 1975; Shishko, Paulson, and Perry, 1977; GAO, 1981a).

GOCO operations are an extreme example of this approach. GOCO arrangements are used extensively in other parts of the logistics establishment, particularly munitions production and distribution. This vehicle might also be used for providing depot-level maintenance support to the services.

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[5]The government does obtain limited data rights when it procures a subsystem. Some rights are necessary to establish intermediate-level maintenance capability, and they are usually sufficient to establish depot capability. However, these limited rights often do not allow the government to provide data to a third party.

[6]There are exceptions to this general rule. Most deal with lower-technology components, although Westinghouse has established a facility with fairly extensive circuit card repair capabilities in Maryland. In general, however, contractors do not appear to be willing to invest in the wide range of capabilities needed to repair the uncertain and generally low repair volumes described in Sec. III.

The primary barriers to investment integration, and particularly to establishing GOCO operations, are organizational and political. The Navy has encountered significant problems in obtaining resources needed to develop organic capability and would probably have even greater difficulties in getting program managers to commit their limited funds to establish a contractor operation. Congressional resistance to replacing civil service with contractor labor would create further constraints (e.g., see House Committee on Post Office and Civil Service, 1977). It may be possible to establish GOCO maintenance operations in the future in spite of these obstacles. However, the primary cost advantages that might accrue from the GOCO alternative can probably be realized by establishing organic capability.

For example, as part of its examination of depot "reposturing" alternatives in the Baseline Study,[7] the Navy recently examined the relative costs of commercial and organic repair for a number of aircraft subsystems. Projected savings from establishing organic capability for components currently repaired on contract ranged from 20 to 90 percent (Moore, 1983). The basis for many of the organic cost estimates was engineering judgment, so it is not clear that all of the forecast savings can be achieved. However, it is unlikely that a GOCO operation could generate substantial additional savings if only half of the projected organic cost reductions could be achieved.

The critical question that must be answered concerning any source-of-repair decision, however, is whether alternative sources can meet operational demands in peacetime and wartime. GOCO facilities would be easier to control than a large number of repair contractors, but are likely to prove less flexible than organic operations.[8] No alternative is viable unless it can satisfy the minimum standard of providing an assured source of repair services to satisfy peacetime and wartime operational requirements, and no alternative to the organic repair option has yet demonstrated this capability.

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[7]The Baseline Study was a large-scale effort to improve estimates of depot-level maintenance capacity requirements as part of a larger effort to develop the Navy's depot modernization program.

[8]There is no physical reason to prevent GOCO operators from being as flexible as organic facilities. However, additional communication

Civilian end-strength constraints, inadequate attention to depot equipment requirements during weapon acquisition programs, and previous DoD guidance to contract out depot-level work have combined to produce the current workload distribution across organic and contractor facilities. This workload mix may not be consistent with wartime support requirements and is probably not "efficient" given that cost comparisons of alternative organizational arrangements should be made for a particular level of output that considers these requirements.

At present there appears to be both operational and economic justification for using organic facilities to repair the majority of the components needed to support modern aircraft. Obtaining the data needed to increase competition in the repair business would weaken many of the economic arguments, particularly if the government made the capital investments for repair contractors.

However, the ability of the service to control organic facilities and reassign priorities among competing resource demands could give such facilities an advantage even in a competitive market. Realization of the full potential benefits of facilities subject to service control will require improvements in both transportation/distribution and depot performance. Additional work is needed to identify the means for improving system responsiveness and guide repair-source-selection decisions once data rights issues are resolved.

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delays would be incurred if changing priorities required changes to a repair contract. A formal mechanism for reordering priorities would probably be necessary to avoid breaching "personal services" contracting rules.

Appendix A

POLICY FOR ACQUIRING COMMERCIAL/INDUSTRIAL SERVICES
NEEDED BY THE GOVERNMENT

Government policy concerning the use of contractor vs. organic
sources to provide essential goods and services is articulated in OMB
(1983a). The general policy statement begins with the observation that
"In a democratic free enterprise economic system, the Government should
not compete with its citizens." It goes on to identify three policy
precepts:

- Rely on the private sector;
- Retain certain governmental functions in house;
- Aim for economy, using cost comparisons where private
  performance is feasible and no overriding factors require
  in-house performance.[1]

The thrust of this policy is clear: The government should rely on
the private sector unless there is some compelling reason to retain
in-house capability to perform specific functions. Renewed emphasis on
this longstanding policy has resulted in considerable pressure on all
government agencies to increase their reliance on the private sector for
commercial/industrial-type activities.

Maintenance services, including depot-level maintenance of aviation
components, are subject to the provisions of the government's policy.
However, several exceptions to the policy outlined in the OMB circular
can be and are used by all of the military departments to justify
organic depot maintenance capabilities. The legitimate exceptions to
this policy identified by OMB are:

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[1]Although the basis for the policy is that the government should
not compete with the private sector, this "precept" suggests that such
competition is not justified *unless* it can be shown that in house
sources can win the competition on price.

- No satisfactory commercial source available;
- National defense;
- The government would incur higher costs if private rather than in-house sources were used.

The second exception constitutes the primary rationale for the existence of organic maintenance facilities. The services' desire to maintain organic capability, however, is reinforced by political pressures applied because most depot maintenance complexes are major employers in their areas. Congress generally has not been supportive of efforts to increase the level of contractor support for functions currently performed in-house (Senate Committee on Armed Services, 1977; House Committee on Post Office and Civil Service, 1977), and the methods used to compare organic and contract costs have been criticized (General Accounting Office, 1981b).

There have been some efforts to direct additional contracts to commercial concerns, notably in legislation concerning use of small and disadvantaged business. This legislation does not deal specifically with repair contracts and, for reasons that will be discussed later, few of these "targeted" firms are in a position to perform component repair work.

Some elements of Congress, with the support of the GAO, have encouraged establishment of a single Aviation Depot Maintenance command to serve all of the military departments (GAO, 1973; GAO, 1978; House Committee on Government Operations, 1983). However, for a variety of reasons,[2] the services have retained the bulk of organic workloads in their own facilities and resisted efforts to establish a single DoD organization.

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[2]Many believe the most important of these reasons to be service parochialism (e.g., see House Committee on Government Operations, 1983). However, there are a number of strong arguments against the establishment of a single manager for ADM, particularly in the short term. For example, Rice (1981) has noted that depot maintenance is only one part of service logistic systems, and these systems should be integrated vertically (across echelons of maintenance) before action is taken to integrate them horizontally (across services).

DOD GUIDELINES FOR SIZING ORGANIC DEPOT MAINTENANCE FACILITIES

The Office of the Secretary of Defense (OSD) has issued amplifying guidance that addresses specifically the issue of repair-source selection and organic maintenance facility sizing (OSD, 1982). This guidance is contained in DoD Directive (DoDD) 4151.1 and requires use of a "decision tree" to select the repair source for specific workloads. If a "tree" logic has not been approved by OSD, the instruction requires that:

- All workloads that cannot be characterized as "mission essential" should be contracted out;
- At least 30 percent of "mission essential" workloads should be accomplished on contract.[3]

DoDD 4151.1 also authorizes the services to size their depot maintenance facilities to permit peacetime organic workloads to be accomplished using one shift on a forty-hour workweek. This rule intentionally provides "slack" in both capital use and manhour availability to support major expansions in output during mobilization.

This "slack" is sometimes viewed as an indication of inefficiency and a reason for consolidating depot management responsibilities across services (House Committee on Government Operations, 1983).[4] However, supporting peacetime training operations is not the primary mission of the service depots. In fact, one of the most important questions that must be answered when contractors are used to perform workloads that can be expected to increase in wartime is whether these contractors have the surge capability that will be needed in time of war.

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[3] The second of these guidelines is admittedly arbitrary and has been criticized both by the services and by the GAO (1976). Service applications of source-selection decision trees have generally shown greater requirements for organic capability than would be authorized by strict application of these two rules.

[4] The aggregate capacity measures cited in the committee report imply that there is excess ADM capacity in service depots. Such aggregate comparisons are misleading, because specific elements of capacity are not fungible across a wide range of workload requirements.

THE A-76 POLICY AND DEFENSE ADM PROGRAMS

As was noted above, "national defense" is most commonly cited as
the rationale for establishing organic service maintenance facilities.
The services generally prefer to use organic maintenance facilities
because they are:

- Easier to control;
- Perceived to be more flexible and responsive than contractors;
- Considered less expensive than contractors;
- Reliable providers of the residual capacity needed to expand
  from peacetime to wartime production.

The control and flexibility arguments are predicated on a belief
that the owning service is in the best position to exercise the control
needed to rapidly reallocate in-house depot repair resources to meet
emergent (peacetime and wartime) operational support requirements. This
capability derives from two attributes of the organic system:

- The service's ownership of the repair facility;
- The scope of repair of the organic depot.

The ability to flexibly reallocate resources to reduce response
time could prove critical in wartime. It could facilitate "coupling"
the echelons of the logistics system to make them responsive to the
needs of the operational forces. Such "coupling" requires:

- An information system to advise the repair activity which
  components are particularly critical;
- Flexibility in resource allocation;
- A responsive transportation and distribution system to move
  components:
    - *To* the repair facility;
    - *From* the storage or repair location to the places
      that they are needed to support operations.

The arguments for service control of the logistics base are summarized in Gracie (1983). The twin issues of control and flexibility also underlie a service proposed set of criteria for deciding which functions should be performed using organic labor (Air Force Logistics Command, 1979). These criteria include:

- Criticality of the activity/function;
- Significant change from peacetime to projected wartime workload;
- Differences in peacetime and wartime functions;
- Operational requirements for responsiveness;
- Management of governmental functions.

Appendix B

ADDITIONAL DATA ON COMPONENT CHARACTERISTICS

The data presented in Sec. II indicate that demand rates for most components, particularly at the depot level, are quite low. This appendix provides additional detail on the low demand problem, and splits the demand data between WRAs and SRAs.

Figure B.1 shows the I-level demand distribution of WRAs installed on the sample aircraft and Fig. B.2 the distribution for the SRAs needed to repair these WRAs. The BCM categories are defined as they were in Sec. II. As we might expect, WRAs have both higher average demands and lower BCM rates than SRAs.

Demand rate

Fig. B.1 -- WRA demand distribution at the I-level

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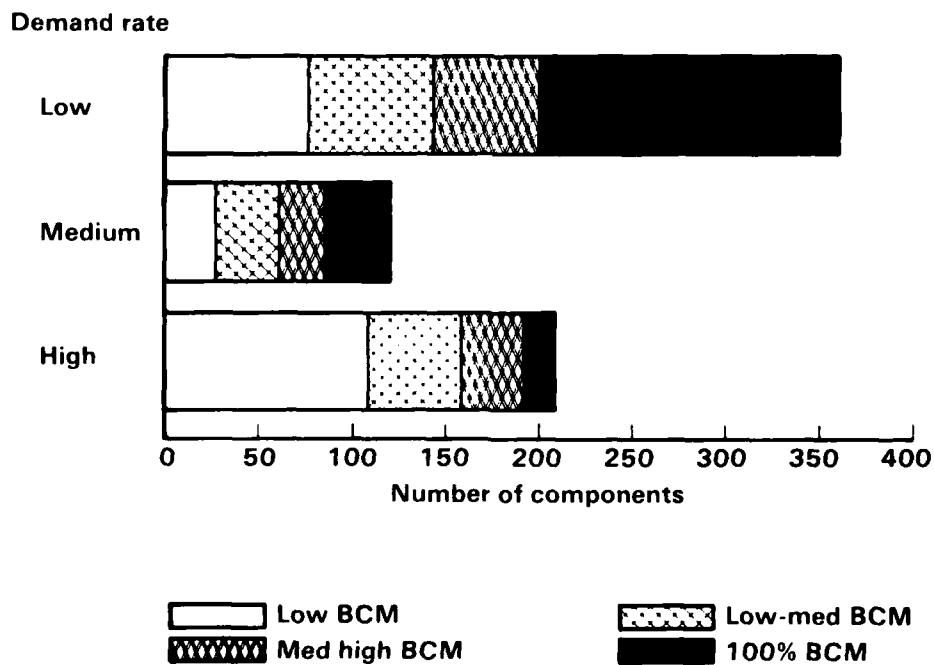
Demand rate

Fig. B.1 -- WRA demand distribution at the I-level

Demand rate

Fig. B.2 -- SRA demand distribution at the I-level

Figures B.3 and B.4 show the number of WRAs and SRAs by equipment
category as well as the expected I-level and depot demand rates within
each category. The range of SRAs is much broader than that of WRAs, and
SRAs tend to have particularly low levels of demand.[1] This implies that
component-specific requirements for manpower, test equipment, and
material tend to be small. It also suggests that a maintenance
structure that supports use of resources fungible across a range of
items is likely to be more efficient than one dealing with only a
limited range of items, since average use rates for these resources will
be higher.

_____

[1]A failure of any of the SRAs installed in a WRA is likely to lead
to a WRA removal; hence, WRA demand rates should exceed those for SRAs.
According to these data, about 60 percent of the total units expected at
the depot are WRAs. There are about 1.5 times as many SRAs as WRAs
installed, so clearly demand levels for most SRAs are extremely low.

- 56 -
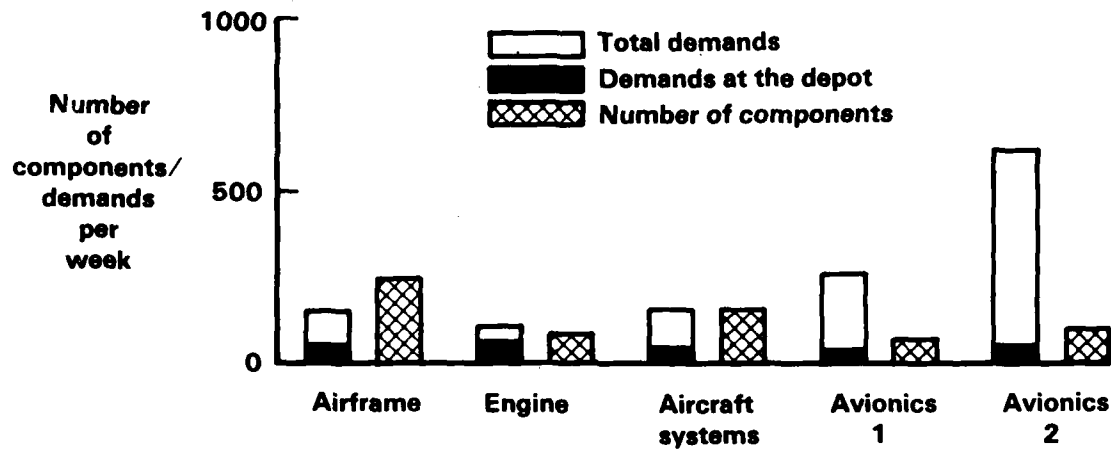
Fig. B.3 -- WRA component and demand distributions
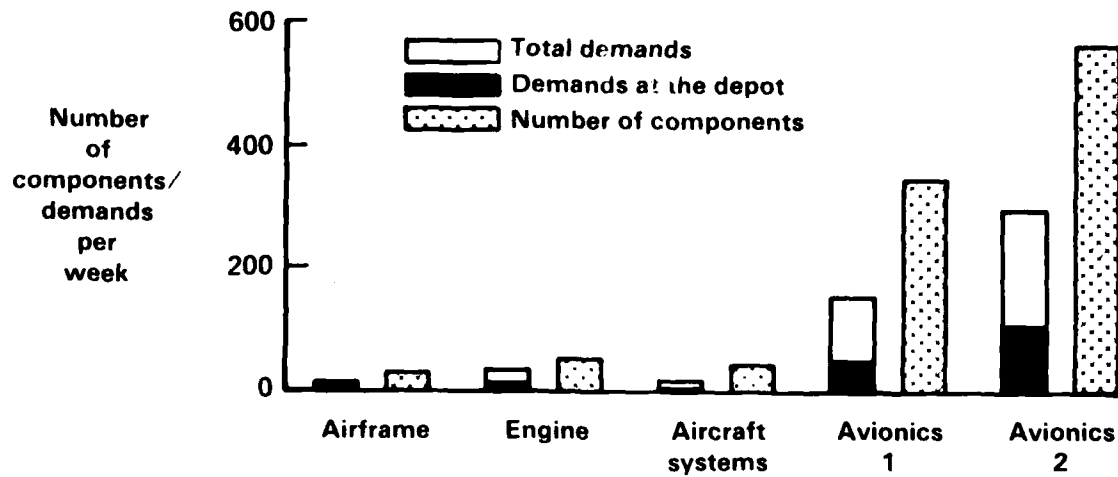
Fig. B.4 -- SRA component and demand distributions

Tables B.1 and B.2 provide a further breakdown of the cross-tabulation of demand and level of technology provided in Table 1. These tables make it clear that:

- Multiple indenture structures become increasingly common as the level of technology increases;

Table B.1

WRA DEMAND AND LEVEL OF TECHNOLOGY

Depot Demand	Degree of Sophistication			
	Low	Medium	High	Total
Low	333	45	121	499
Medium	50	20	54	124
High	25	10	26	61
Total	408	75	201	684

Table B.2

SRA DEMAND AND LEVEL OF TECHNOLOGY

Depot Demand	Degree of Sophistication			
	Low	Medium	High	Total
Low	61	296	542	899
Medium	14	43	51	108
High	0	7	28	35
Total	75	346	621	1042

- SRA demand rates are particularly low;

- Providing support capability for a wide range of such low demand items, particularly if arrangements cannot be made to "share" resources across components, can quickly become an extremely expensive proposition.

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Appendix C

MODELING THE EFFECTS OF LOGISTICS SYSTEMS PERFORMANCE
ON WARTIME AIRCRAFT AVAILABILITY

In addition to influencing the mix of resources needed to support wartime demands, reducing pipeline times can contribute to increased wartime aircraft availability, particularly in the face of an uncertain demand stream. Rand's Dyna-METRIC model was used to estimate these effects.

Dyna-METRIC is an analytic, stochastic, and dynamic model that relates aircraft flying to logistics resources like repair, distribution, and supply. Most applications assume that component demand is generated by a simple Poisson process, although other distributional assumptions can be used, and that demand is a linear function of flying intensity.[1]

Additional assumptions reflected in the results presented below are that:

- Demand and BCM rates are "known" constants;
- Repair and distribution delays are exponentially distributed about their expected values;[2]
- These critical peacetime parameters can be extrapolated to wartime activity levels;
- Components are cannibalized[3] to minimize the number of aircraft down as a result of missing parts at each location.

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[1]The Dyna-METRIC model is described in Hillestad and Carrillo (1980), Hillestad (1982), and Pyles (1984).

[2]Fixed delays can also be used.

[3]Cannibalization involves using aircraft that are "down" for other reasons as a source of supply for critical components.

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OPERATIONAL IMPACTS OF DEPOT-LEVEL SUPPORT

How quickly the depot system can respond to operational force
demands determines when and how much depot repair can affect aircraft
availability. For example, Fig. C.1 illustrates an upper bound on depot
contribution to aircraft availability if a component must go through a
retrograde, repair, and shipment time before it can be returned to an
operating location. That is, the figure assumes *no stock* but adequate
repair capacity at the depot. The upper curve (a) shows projected Not
Mission Capable-Supply (NMCS) aircraft for current pipeline times, which
average about 140 days.[4] Curves (b) and (c) show the effects of
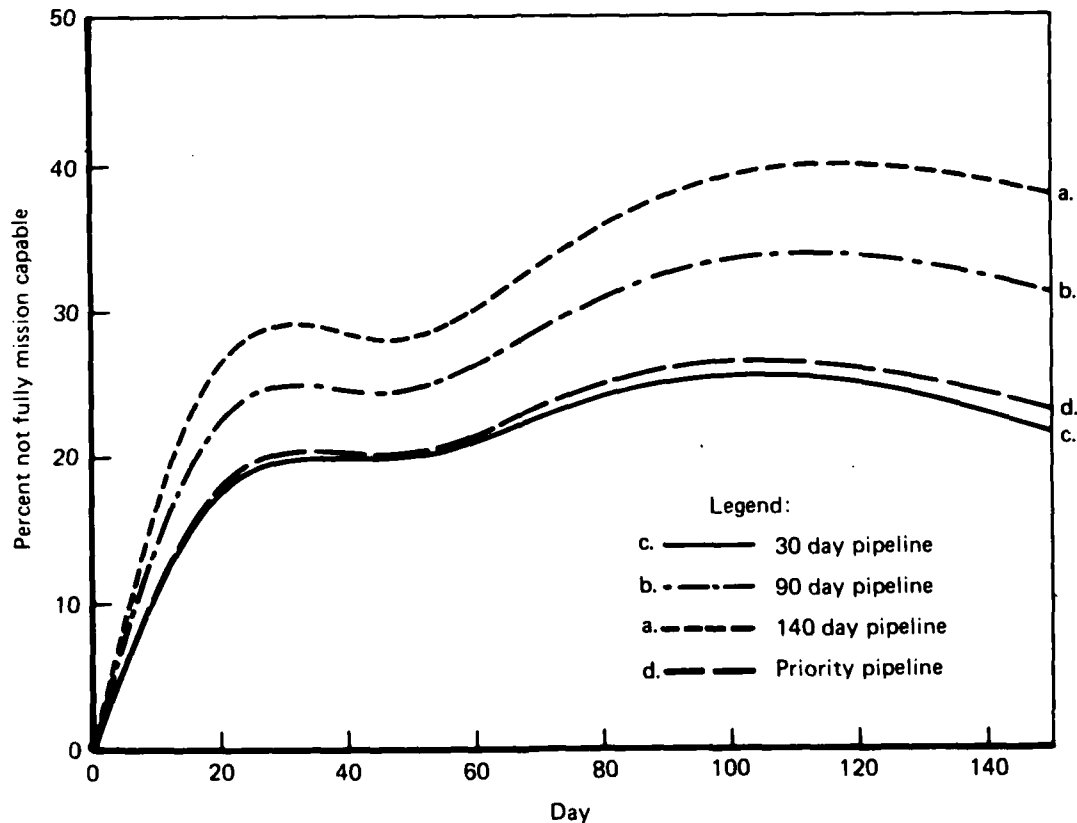reducing pipeline times to 90 and 30 days, respectively.

Fig. C.1 -- The effect of logistics delays on aircraft availability

[4]Current peacetime retrograde and shipment times from and to
carriers have been estimated at about 60 days and 30 days, respectively
(Johnson, 1981). Figure 6 suggested that depot repair times average
about 50 days.

All of these curves consider only the effects of WRAs that can be repaired using the Versatile Automated Systems Test (VAST) equipment;[5] including other components would increase the expected percentage of aircraft that are NMCS at any point in the scenario. Nonetheless, even though the "no stock" assumption is not realistic, the curves demonstrate that shortening pipeline times would increase aircraft availability.[6]

It may not be possible to reduce average depot pipeline times to 90 days, to say nothing of 30 days. However, the system can and does provide priority service to a few components. Curve (d) in Fig. C.1 shows that it is not necessary to reduce average pipeline times for all components; approximately the same effects can be realized by reducing total pipeline times for the components most likely to degrade aircraft readiness.[7]

In other words, expediting the shipment and repair of selected problem parts can yield most of the benefits of expediting components across the board. This occurs because some parts--those that fail more frequently than others or require more depot-level repair--"drive" aircraft availability. These "drivers" will cause the majority of NMCS

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[5]This group of components was selected because VAST provides a particularly good example of a fungible repair resource that can make use of priority scheduling rules. This equipment can be configured to test over 400 components--both WRAs and SRAs--used on four different types of aircraft.

[6]Pipelines could also be shortened by maintaining considerable slack repair capacity. This alternative would be quite costly. Capacity sizing criteria, which are reflected in test equipment design practices, should stress the need for *efficient* as well as *responsive* repair.

[7]This example divides the components into three groups on the basis of their predicted effects on aircraft availability. These groups, and the assumed pipeline times, are:

Component Group	Pipeline Time
Top 20%	30
Next 20%	60
Remainder	140

incidents[8] during wartime even though stockage levels will attenuate
their effects. Hence, they should receive more attention than other
components throughout the system, especially if total repair capacity is
constrained.

THE OPERATIONAL PAYOFF OF PRIORITY REPAIR

Reductions in total pipeline times can be achieved by reducing any
of the elements of this time, i.e.:

- Retrograde distribution time;
- Depot repair cycle time;
- Order and ship time.

Transportation times are often longer than depot repair times, and
the depot cannot fulfill its support role until repairable carcasses are
delivered by the transportation system. Hence considerable effort to
reduce distribution times, particularly retrograde times, is warranted.
However, depot management cannot influence distribution times directly.
It can, however, affect the length of the depot repair cycle.

Repair scheduling is the depot manager's most powerful tool for
increasing the contribution of depot repair to wartime operational
support. If depot repair capacity constraints make it impossible to
satisfy all wartime demands, available capacity can be allocated to
satisfy only those demands that will make the greatest contribution to
aircraft availability. Implementing such priority scheduling rules
requires:

- An information system that identifies critical requirements;
- A means for forecasting future critical repair requirements;[9]
- Fungible repair resources that can be focused on the components
  that are or can be expected to become critical.

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[8]The term "NMCS incident" refers to a "hole" in an aircraft that
cannot be satisfied from local stockage or repair.
[9]Satisfying today's requirements may not address those likely to be
encountered in the future.

Figure C.2 shows the percentage of aircraft degraded by lack of
VAST-repairable WRAs under two alternative scheduling rules on the
assumptions that: (1) The I-level has ample repair capacity, i.e.,
wartime BCM rates do not increase above those observed in peacetime; and
(2) there is insufficient depot repair capacity available to satisfy all
depot repair requirements.[10] The upper curve is based on application of
a first-come, first-served rule. The lower curve shows the result if
the scheduling algorithm is changed to emphasize repair of components
making the largest expected contribution to aircraft availability, i.e.,
priority repair. Both curves assume that cannibalization is used to
maintain aircraft availability.
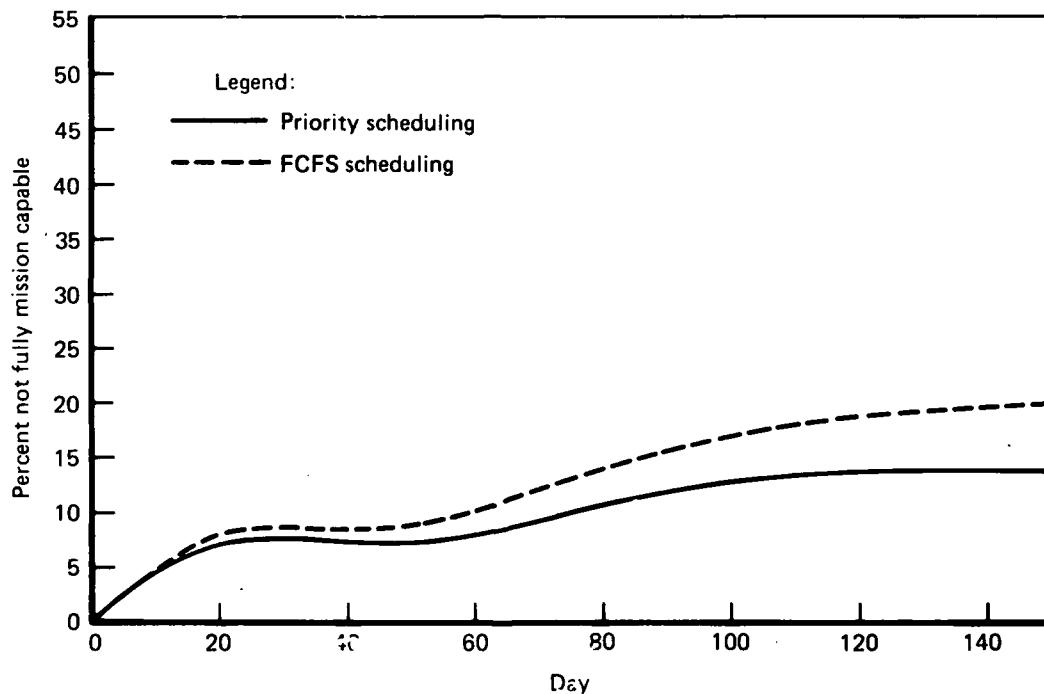
Fig. C.2 -- The effects of alternative VAST scheduling rules
when the I-level has adequate repair capacity

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[10]The discussion in Sec. III suggested that depot repair capacity
is unlikely to constrain aircraft availability unless wartime demand or
BCM rates increase. This and subsequent illustrations assume that depot
capacity is constrained to illustrate the effects of alternative
scheduling rules. The capacity issue is discussed further in Moore,
Embry, and Dey (1985), but it was not the intent of either study to
evaluate the adequacy of current depot capacity.

Figure C.3 compares the second case above to one in which VAST capacity is limited at both the shore stations[11] and the depot. Priority repair is employed in both examples. The assumed limitation in I-level repair capacity increases the total demand for depot-level repair. Since depot capacity is assumed to be insufficient to satisfy even the increase in demands associated with an increased flying program, the increased shortfall in depot repair capacity further degrades aircraft availability.
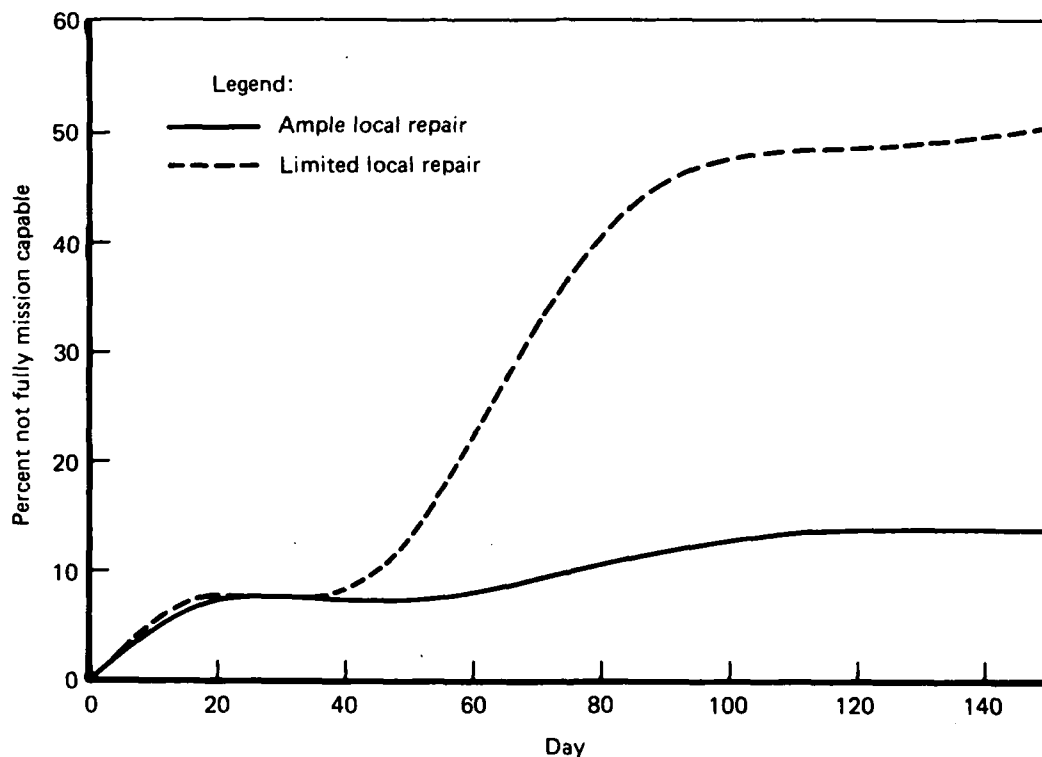
Fig. C.3 -- The effect of I-level repair capacity constraints

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[11]This example was constructed because some test equipment inventories are insufficient to outfit all carriers and shore operating locations. The Navy's normal procedure in such cases is to transfer equipment from shore locations to the carriers, which would increase BCM rates at the shore stations to 1. Similar effects would result if all locations had their allowance of test equipment but there was a wartime I-level repair capacity shortfall.

- 65 -

Figure C.4 compares the impacts on the depot with current and reduced distribution times when VAST capacity at both the intermediate and depot level is insufficient to satisfy all repair demands. The lower curve shows the effect of reducing average distribution times to one fourth those experienced in peacetime.[12] The results shown confirm those suggested in the surge workload analysis: reducing distribution times permits the depot to play a more significant role in providing wartime support.
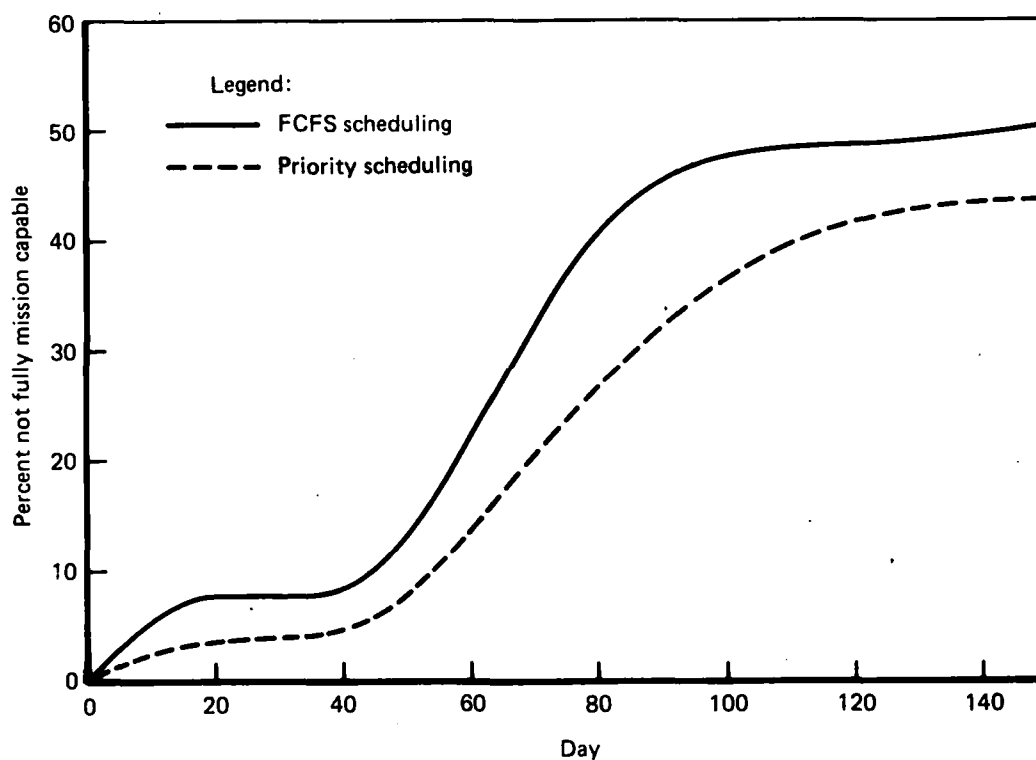
Fig. C.4 -- Priority repair and reduced transportation times: combined effects

[12]Transportation times for all components have been reduced for this example. Figure C.1 suggests that this is approximately equivalent to reducing distribution times only for those components most likely to cause NMCS incidents.

Reducing distribution times does not, however, guarantee improved
performance. Figure C.5 contrasts the NMCS rates that can be expected
to result if FCFS rather than priority scheduling rules are used at the
depot; both cases assume that distribution times are 25 percent of those
experienced in peacetime. Improved transportation and distribution can
improve wartime aircraft availability--but the full benefits occur only
if depot management takes action to reduce its contribution to total
pipeline time.

These examples illustrate the payoffs of priority scheduling rules,
which can be used most effectively by facilities that can share
resources across a broad range of components, i.e., those having broad
scope of repair. The benefits of priority repair can be realized most
easily if a single repair facility has responsibility for repair for a
range of components that share similar resources. For a system with a
fixed level of repair capacity, the aircraft availability delivered by
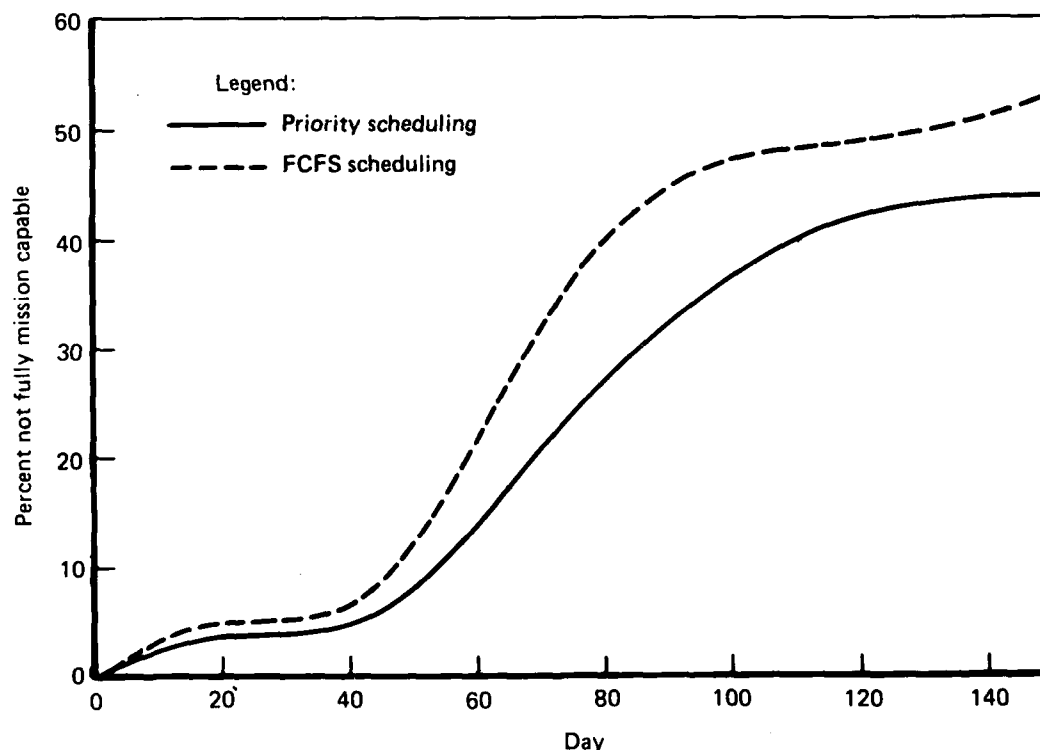
Fig. C.5 -- FCFS vs. priority scheduling with reduced transportation times

the support system will decrease as the number of repair locations increases, because scheduling will more nearly approximate FCFS than a priority rule. Appendix D provides a further indication that reducing the number of repair locations, which could also increase scope of repair, can be expected to provide operational payoffs.

Appendix D

OTHER OPERATIONAL IMPLICATIONS OF ALTERNATIVE
LOGISTICS SUPPORT POSTURES

One additional advantage of centralizing repair resources is a resulting simplification in communication and distribution problems. Currently each operating location ships BCM components to the Designated Overhaul Point directly. Many components are shipped by mail.

The component distribution problem is analogous to that of designing a communications network to pass messages from m transmitting to n receiving locations. If the network is designed to permit each transmitter to communicate directly with each receiver, $m \times n$ channels are required. However, if all messages are routed through a central distribution point, only $m + n$ channels are needed. Kleinrock (1964) has shown that the structure with the minimum number of channels minimizes communications delays if total channel capacity is limited. The number of channels can be minimized by routing all traffic through a common distribution point and reducing the number of senders or receivers.

The number of points that must ship retrograde cargo and receive serviceable shipments is fixed for combat reasons. However, the complexity of the distribution network can be reduced by reducing the number of activities involved in performing depot-level repair.

Although distribution channel capacity is not limited in peacetime, it is likely to be during a war. Even if physical distribution capacity was infinite, aircraft turnaround time constraints would operate to make much of it unavailable. In addition, reducing the number of distinct distribution channels would facilitate shipment consolidation and simplify the problem of tracing shipments.[1]

Kleinrock's result also has implications for the logistics command, control, and communications problem. Communicating priorities to a number of separate repair points would pose a much more difficult

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[1]There is greater potential for shipment delays and losses in a structure with multiple channels. This is particularly true if mail is the mode of shipment, because mail shipments cannot be traced.

problem than presenting this information to a smaller number of suppliers.

In summary, it is more difficult to manage a communications or a distribution system with multiple shipment channels and sources of repair than one with fewer links and nodes. Reducing the number of repair points in the system, and changing current distribution rules, would simplify the component support management problem.

The basic problem can be stated as follows: M oversees local repair facilities ship plane parts that cannot be fixed locally to one of N depots within the United States. Parts are not identical: a given part must be sent to a specific kind of depot. The objective is to find a network structure that would minimize transportation delays and losses between the M local facilities and the N depots.

Extensive theoretical work has been done by Kleinrock regarding the transportation delay problem, but the theory does not say too much about losses. Both problems are addressed below.

MINIMIZING DELAYS

The two basic questions are:

1. Which is the better structure:
   a. A network where each of the M local repair facilities has direct access to each of the N depots;
   b. A network where each of the M local repair facilities ships parts to a central location, which redistributes the parts to the appropriate depots.
2. What is the optimal number of depots?

Note that the number of local repair facilities, M, is fixed. It cannot be reduced, otherwise some facilities would not be local anymore.

The networks described in (1a) and (1b) are shown graphically in Fig. D.1.

This delay minimization problem can be approached like a communication network problem in which messages can be sent from M origins to N destinations. Given a fixed total capacity, the problem is to find the optimum assignment of channel capacities in a network with M

a.

b.

Local
facilities

Depots

Local
facilities

Depots
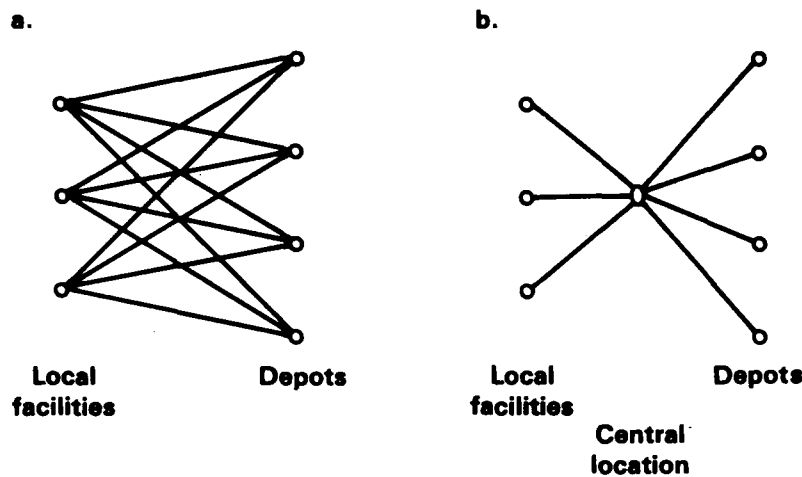
Central
location

Fig. D.1 -- Repair network alternatives

origins and N destinations. In both structures (1a) and (1b), queueing
might occur at the local repair facilities and the depots, and in (1b)
queueing might occur at the central location as well.

Kleinrock (1964) studied this problem in a communication network.
His general conclusion was that:

- *Delay is minimized in a queueing process when traffic is
  concentrated in as few channels as physically possible.*

Kleinrock's results rely on a set of assumptions that must be true
for the repair system network if they are to be applied to the repair
problem. They are:

a. Arrivals into the system must follow a Poisson distribution.
    Arrivals of parts that cannot be fixed locally are random at
    any of the local facilities. Furthermore, the arrival of one
    part that cannot be fixed locally does not affect the
    probability of arrival of another part that cannot be fixed
    locally. These two statements define a time-dependent Poisson
    process. Hence, arrivals of parts that cannot be fixed locally
    follow a Poisson distribution at any local facility.

b. Processing times are assumed to be exponentially distributed. Kleinrock shows that they can be assumed to be exponentially distributed even if this does not correspond to the real situation; the model still accurately describes the message (processing time) behavior in many real networks when the "observed" and "assumed" distributions differ.

c. The sum of the assigned channel capacities is constant. This hypothesis is very important in Kleinrock's capacity assignment. It matches exactly the constraint self-imposed on the repair system network under investigation. The total channel capacity (i.e., total shipping capacity) is given, primarily because the system's ability to introduce traffic to the system is limited.

Assuming that these assumptions are true for the repair system network, Kleinrock's general conclusion can be used to choose between structures (1a) and (1b). Traffic is concentrated in M + N channels in structure (1b), which is less than in the M x N channels of structure (1a). Delay is minimized in structure (1b) with a central location: Structure (1b) is better for the repair system network.

The second question for this particular structure can be stated as follows: what is the optimum number of depots, i.e., the optimum number of channels emanating from the central location?

Kleinrock's results can be applied to the subnetwork comprising the central location and the depots represented graphically in Fig. D.2.

Arrivals of parts that cannot be fixed locally constitute a time-dependent Poisson process at any of the local repair facilities. Let k_i be the average arrival rate at the ith facility. We assume that these parts are forwarded to the central location at the same rate. The central location receives parts from M local facilities according to M independent Poisson processes with respective average arrival rates k_1, $k_2, \ldots, k_M$. Independent Poisson processes are additive: parts arrive to the central location according to a Poisson process with average arrival rate

$$\sum_{i=1}^{M} k_i$$

**Central
location**   **Depots**
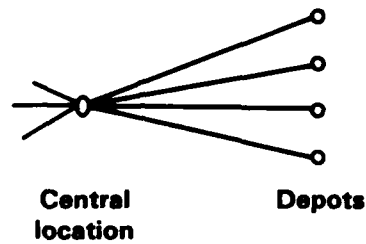
Fig. D.2 -- Subnetwork connecting a central location and depots

Processing times between the central location and the depots are assumed to be exponentially distributed.

Let C be the total given channel capacity of the network between the central location and the N depots, C/N being the capacity of each channel. C and C/N are expressed in numbers of parts per unit of time (e.g., number of parts per day or per week).

Parts arriving to the central location form a queue, the discipline of which is first-come, first-served.

Given the above assumptions, Kleinrock shows that the value of N that minimizes overall delay in N channels leaving a single-node facility is N = 1.

Obviously other factors must also be considered when defining the structure of the support system. These include:

* Its vulnerability;
* The total size of the facility or facilities;
* The proximity of the facility or facilities to transportation system nodes.

However, the analytic result has the following interpretation:

* *Other things being equal and given a total channel capacity, the repair system network should be designed with as few depots as physically possible.*

MINIMIZING LOSSES

The literature does not say too much about losses within a network.
The general assumption is one of conservation, i.e., nothing is lost.
There are two exceptions. The first concerns a system in which the
elements traveling are human customers discouraged by an excessive
queue. They may choose to drop from the system after entering it, but
before being processed. The second is closely related to the first:
When a queue forms at any node of the network, there must be enough
storage capacity to hold the expected maximum number of waiting goods.

In the repair system case, the central location must include a
warehouse large enough to hold the expected maximum number of waiting
parts that can be sent by the local repair facilities. This expected
number can be derived from observations of the current system. If the
central location warehouse is not large enough, some losses might be
expected because some parts might have to wait "outside" the central
location before being processed. The risks of losses by overcrowding of
depot warehouses can be minimized by careful management of the central
location: A part can be sent to a given depot by the central location
after checking that the depot is ready to get the part to either
temporarily store it or to fix it.

Similar losses are conceivable at the local repair facilities if
the flow of parts out of a given facility to the central location is
equal to the shipping line capacity. If no adequate storage and
handling facilities exist at the local level, parts might get lost
before being sent to the central location.

The only reference identified that deals with losses along the
communication channels themselves is not of very practical use. It is
the inclusion of an unreliability component in a cost function to be
minimized with respect to network parameters, e.g.:

$$\text{MIN} \sum A \times T + B \times U$$

(capacity assignment)

(network structure)

where A and B represent some dislike coefficients for time processing delay T, and U represents unreliability. The function must consist of an appropriately defined measure of unreliability in both channels and nodes. In other words, the above cost function is hardly usable in any practical application.

Appendix E

ECONOMIC ANALYSIS OF ALTERNATIVE REPAIR SYSTEMS

This appendix outlines conceptually the economic problem of selection and operation of repair facilities. A model based on this outline could be used to contrast a variety of possible strategies and performance measures. Several important considerations affect the analysis and are worth stressing at the outset.

First and foremost, the acquisition of technical information relevant to the diagnosis and repair of equipment is of paramount importance, because efficient repair obviously requires access to such information. In addition, the right to use such information can be of vital importance in managing the contractual relations governing equipment supply and maintenance. This fact has implications for both the form and content of procurement and repair contracts. At the same time, the pivotal role of information has an impact on the conduct of repair operations, since technical information will emerge during the lifetime of the product as improvements are made and repair facilities move down the "learning curve." In addition, although information about specific repair processes is probably relevant only to particular weapons systems, knowledge of technology is at least partially transferable between weapons systems, especially for general purpose test equipment.

The second major observation is that the fixed costs of acquiring test equipment are likely to be significant. Again, the ramifications are twofold. At the informational level, this fixed cost argues in favor of integrated test equipment, which in turn implies that a single diagnostic system (such as the VAST) may have to have the capability to handle software associated with the products of many manufacturers. This in turn combines with the proprietary nature of much of the technical data to favor in-house repair facilities. At the same time, the economically motivated reactions of firms must be taken into account. For example, a firm may meet demand for repair services by adapting production equipment. Alternatively, a firm with a large

investment in test equipment may adapt such equipment for use in production processes. If properly managed, this diversion could provide a cheap way of ensuring that the excess testing and repair capacity required to meet demand surges is present in the system.

However, the joint use of equipment in repair and production is not without costs. The two functions are significantly different, and the resulting system (which includes hardware, software, and learned human capital) will not be ideally suited to performing either role efficiently. In addition, under wartime conditions there will be competition for existing capacity between repair and new production, and it is not clear that this will be resolved efficiently under private incentives. Therefore, encouraging private firms to develop their own testing and repair facilities may have its pitfalls. Furthermore, firms may require financial assistance in forming the necessary capital. The possibility for abuse requires that some sort of performance-related contractual scheme be used to monitor contractual performance. This in turn raises questions related to the transferability of test capital between firms. Different rules regarding the ability to recover fixed costs in the event of a change of repair facility[1] will affect:

- Repair costs;
- The extent and distribution of learning-based cost savings;
- The amount of excess capacity retained by the system for meeting surges.

There are additional long-range implications for procurement cost, intersystem compatibility, integration, etc.

This appendix is divided into three parts. The first discusses the implications of the fact that many criteria must be used in measuring the success of programs designed to manage supply or repair processes. The second takes up the question of information. This includes information about the demand for repair services, the supply of repairs stemming from the original design of the weapons system, and supply

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[1] Three obvious alternatives are: (1) privately owned, fully transferable repair capital; (2) privately owned, nontransferable repair capital; and (3) GOCO facilities.
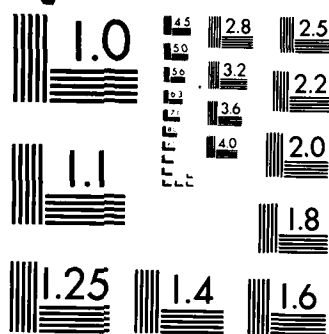
MICROCOPY RESOLUTION TEST CHART

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information arising during the system's lifetime, resulting from repair experience or design changes. The third part outlines an approach to analysis of the incentives created by alternative contractual arrangements.

PERFORMANCE MEASURES

Perhaps the most striking feature of the repair problem is that there are many different possible measures of success or failure from the Navy's point of view, and no obvious way to combine them into a single "bottom line" number. This stands in sharp contrast to the situation of private firms engaged in production and possibly repair. The fact that the Navy has such a "multiattribute utility function" while its contractual partners do not affects the ultimate decision of the Navy on organic versus contractor-supplied repair.

Private Firms

The demand for repair services is uncertain. It is affected by global considerations such as the level of operations and the probability or nature of a state of war. In addition, system considerations reflect the importance and ease of repair of a given component and the existence of available alternatives such as substitution or replacement. Finally, the lessons of experience may dictate design changes in a particular system, or changes in deployment that make such a system either more or less important than originally envisioned.

In principle, private firms are motivated by the desire for profits. The various factors mentioned above will be viewed in light of the profits of the firm. However, it is important to know when the firm earns profits and the firm's assessment of the uncertainty it faces. Analytically, the firm should act to maximize the expected present value of profits, where "expected" refers to the firm's own assessment of profit or loss, and "present value" means that profits earned in the future are discounted.

The expectations of the firm are conditioned by its information, by its experience, and by what it thinks about other firms and the government. To a certain extent, these expectations can be controlled.

For example, if a firm might be punished for poor performance by the loss of some or all of its contractual repair business, the effect of the threatened punishment will depend on whether the firm believes the punishment will be carried out, and also on how much the firm thinks it can recover if it loses the contract. Therefore, contractual terms committing the government to take away the bad firm's business and regulate the terms under which capital can be transferred to a successor firm are likely to have a large influence on a firm's choice as to whether or not to honor the terms of its contract.

In addition, competition between various possible sources of repair capability can be understood in terms of the expected present value of profits to each firm, together with an additional stipulation as to the nature of such competition. In a highly concentrated and inelastic market, such as the component repair market, the competitive model in which firms take prices as given is likely to be unrealistic, and considerations of strategic behavior, bargaining, and collusion are likely to dominate.

The simplest model remaining after the perfect market assumption is discarded is that of noncooperative interaction. In this view, each firm takes the bidding and performance strategy of the other firms as given, and then computes its "best" reply; the strategy that maximizes the expected present value of profits. An equilibrium is a situation in which each firm makes a best reply to the other firms. This represents the solution to a game in which the firms are players. The government determines the rules of the game, and must take strategic behavior into account when choosing its repair sources. On the other hand, since the government does not have a single objective function, and takes a longer perspective than the firms, it seems best not to make the government just another player in the game.

Naturally, the terms of a contract are set by bargaining, and any changes in terms must be resolved by bargaining. There is a simple theory that predicts the outcome of such bargains in light of the alternatives available to each party. A more sophisticated model would take the role of bargaining into account when specifying the expected profits to firms. Otherwise, the analysis would be similar to the wholly noncooperative model.

Finally, it must be recognized that repair contracts are arrived at in a larger context. This includes procurement arrangements, and is explicitly dynamic. Therefore, the terms of any repair contract must have contingent elements, specification as to what will be done under a variety of possible circumstances. Perhaps more importantly, if technical data and repair volumes are sufficient to promote competition, the same parties will deal with each other in an ongoing game. This ongoing relationship makes collusion quite attractive: Firms supposed to compete for government business face a strong temptation to settle among themselves the identity of the winner and the terms of the eventual contract. These firms can make and police such an agreement, because future profits can be used as a lever to ensure cooperation. At the same time, it is relatively difficult for the government to verify collusion, let alone the extent to which price and performance are affected by it. The nature of the bidding process can, however, be manipulated in such a way as to make collusive arrangements much less attractive.

The Government

The motivation of the Navy is far different from that of private firms and is therefore more difficult to model. There are many dimensions to performance of a weapons system, and the importance of each depends on a complex hierarchy of factors. At the same time, it appears to us that some important simplifications are available. For example, many dimensions of performance can be summed up in the availability of hours of sortie time under various conditions (peacetime, surge) and for a variety of combat and other roles. This measure wraps up a number of adaptive responses on the part of the repair system that may be complex to model. Using the methods of reliability theory and operations research, it is possible to get measures of how crucial a system is likely to be in terms that allow the Navy to interpret contractual and organic repair set-ups in "bottom-line" terms.

On the other hand, this does not completely solve the problem of defining and interpreting Navy motivations, since sortie hours under wartime conditions will probably drop off as combat proceeds. This argues that a relevant variable could be "expected (or discounted) combat sortie-hours," where the discounting represents the simple fact that long-run capability is important only for forces that survive the short run. In addition, discounting can take account of the expected duration of combat and the correlation between duration of combat and expected attrition.

Thus, it should be possible to reduce the "measures of success" to relatively few. These would probably include expected peacetime and wartime sorties and flying hours, complemented by measures of "worst-case" and surge outcomes to take account of important possibilities to which it is difficult to assign probabilities.

Once outcomes can be interpreted in terms of a few variables, the analysis should seek alternatives that are "efficient." This means that any improvement in one measure of success must be paid for by a worsening in other measures. This can be done without making any judgments as to the relative merits of peacetime versus wartime capability, for example.

Although the issue of relative importance must eventually be joined, it seems reasonable to narrow down the possibilities as much as possible acting on first principles. After all, for every inefficient alternative there is one that is better by any standard, so there is no point in considering inefficient possibilities.

From what is already known about "principal-agent"[2] problems, it is likely that all efficient arrangements will have some common features, and therefore these aspects can be incorporated into contractual design up front.

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[2] A principal-agent problem is a model of the strategic interaction between two (or more) parties under conditions of incomplete information. The principal moves first, designing a reward scheme for the agent. The agent moves later, possibly on the basis of information that the principal does not know, and makes a choice (e.g., effort) that the principal may not be able to observe. The result is payoffs to both parties, which are reallocated according to the contract. The essence of the problem is to derive the best contractual forms from the principal's point of view, assuming that the agent will react selfishly.

The basic problem is one of incomplete information, since the Navy would like to have firms disclose (via their bids) information about costs and ability to perform component repairs. Without such information, it is impossible to ensure that contracts will be let to the best firm. In addition, the Navy could not make meaningful comparisons between organic and contractor-operated repair facilities.

A variety of mechanisms can induce truthful revelation of private information. They can be illustrated with a simple example, known as the "second-price" (or Vickery) auction. Suppose that a number of firms with different costs are engaged in a sealed-bid auction for a repair contract, and assume that the terms of the contract offer adequate performance guarantees, so the issues are: (a) finding the lowest-cost firm; and (b) finding that firm's cost, to decide whether to do the repairs in house. If the contract goes to the lowest bidder at the cost it bids, there is a natural tendency for firms to submit inflated bids. If a firm wins a contract with an honest bid, it gets no profit. Under this "first-price" scheme, the contract may go to the lowest-cost firm, but this is not guaranteed. In any event, the cost estimates will be biased upward, and this can distort any decision as to whether to do repairs in-house.

Now suppose that the contract is awarded to the lowest-bidding firm at the second-lowest bid. Under this system, the best any firm can do is to submit its true cost. Suppose the firm's true cost is C, and it submits a bid of B. If it underbids, so the $B < C$, it runs the risk of having another firm bid an amount A, where $B < A < C$. In this case, the firm bidding B "wins" the auction, but is only paid A for services that cost it C to provide. Alternatively, suppose that the firm overbids, so that $B > C$. If another firm bids A', where $B > A' > C$, that other firm will win the contract and will be paid B. The firm that bid B could have lowered its bid (to anything less than A), won the contract, and made a profit of $A' - C$. This shows that each firm's best reply to the other firms is to bid its true cost, no matter what it thinks the other firms are going to do. The result is a truthful revelation of costs.[3] In addition, while the government pays more than the lowest cost under

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[3]This discussion assumes that estimation of costs is quite

this scheme, it pays the next lowest cost. If technology is well
understood, the next-lowest cost is likely to be close to the lowest
cost, and the difference can be shown to be the smallest payment that
will induce truthful revelation. Slight modifications of the mechanism
will also prevent collusion from being profitable.

None of the above should be interpreted as requiring the Navy to
give any repair business to outside contractors. Instead, any
contractual alternative should also be compared to a variety of organic
repair options. This analysis merely creates a framework that allows
meaningful comparisons.

INFORMATIONAL ASPECTS

Proper information flow is essential to efficient performance. It
is necessary to differentiate among three types of information:

- Demand information relating to the type and extent of repair
  services that will be needed;
- Production information relating to the system(s) in question,
  which originates with the supplier; and
- Repair information that arises during the lifetime of the
  system.

Estimates of the nature and amount of excess capacity required to
meet wartime demands will depend on information concerning expected
wartime demand. If the Navy chooses not to disclose this information
for security reasons, the service will need to maintain a substantial
organic repair capability to satisfy increased wartime demands.
However, this need not require an organic repair facility, e.g., the
cheapest way of meeting the surge capacity goals may involve training
Navy personnel in contractor-operated repair facilities.

This comes into sharper focus if the mix of repair needs in wartime
is not a simple scale increase of the peacetime mix. Repair needs
resulting from a different pattern of stresses or from specific
countermeasures may not follow the peacetime pattern. Although they may

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straightforward. As was noted in Sec. IV, in practice this may be a
very difficult problem.

be predictable, information about them may have strategic value. During
wartime it may expose vulnerability to certain countermeasures or
provide evidence of crucial weaknesses. In this case, the service might
prefer to handle the "extraordinary" demands (those which are not simply
a scaling up of peacetime levels) in house.

Production information has several dimensions. There is a strong
proprietary element, and suppliers of equipment have traditionally been
reluctant to part with such information. In addition, the government's
representatives in bargaining over both procurement and repair contracts
have generally operated under an informational disadvantage and have not
stressed acquisition of production/technical information.

On the other hand, such information has a variety of uses. For
example, it could:

- Permit the construction and programming of integrated testing
  systems capable of handling products from many sources, thus
  allowing economies of scale in repair;
- Free the Navy from dependence on single-source repair
  facilities--dependence that can result in inefficient
  substitutions and poor system flexibility;
- Allow the Navy to award repair contracts on the basis of repair
  performance, rather than as an additional bonus for winning a
  procurement contract;
- Discourage firms from winning procurement contracts using
  designs that shift the costs of a system from production to
  repair;
- Secure performance on both procurement and repair contracts by
  increasing the risk of losing repair business, since the
  proprietary value of such information makes its disclosure to
  alternative contractors and potential competitors something a
  supply/repair contractor would wish to avoid.

In sum, even an organic repair facility should be able to take
account of technical data to operate efficiently, and performance on
both supply and repair contracts is likely to benefit from Navy
acquisition of such information. What remains to be seen is the extent

to which competition will reduce the price at which the Navy can obtain the information. If organic repair is the chosen option, it may be sufficient to acquire the information without acquiring the right to disclose it to other firms. This should be much cheaper, since the supplier's proprietary interest in keeping information out of Navy hands is reduced, and disclosure for government use is a common contractual requirement.

Finally, the information that is acquired in the course of conducting repairs is of crucial importance to controlling lifetime costs of a weapons system. The cost of maintaining a given level of performance will fall along a "learning curve" as the system matures, and it is important that these cost savings be retained if the repair contract changes hands, or in the face of surges in demand. Most of this knowledge is embodied in human capital, which suggests that a certain degree of excess capacity is required in the workforce.[4]

The implication for repair contracting is that any potential repair facility should be represented in the workforce of an active repair site. If the repairs are performed by contractors, Navy personnel should form part of the workforce, perhaps on a rotating basis. This will provide a trained corps of repair personnel in the depot who can meet surge repair requirements or assume the burden of normal repairs in the event of poor contractor performance. In the same way, if an organic facility is desired, a certain degree of rotation through the repair facility will provide surge capability. However, it may be that private contractors will have a greater incentive to generate efficiencies and cost savings, particularly i their informational monopoly power is constrained by the obligation to share what they learn with Naval personnel.

MODEL DEVELOPMENT

The preceding discussion has touched on many of the considerations that should be treated in analyses of alternative contractual arrangements. However, this conceptual outline is not sufficient to specify a model of the contract vs. organic decision. Such a model could be used to structure repair facilities to meet the evolving needs

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[4]Labor constraints on capacity can be relaxed by using overtime.

of the Navy, together with contractual forms that will ensure that self-interested behavior by firms will match Naval expectations.

The first task is the analysis of a baseline case representing the best possible performance. To obviate issues of cost and incentives, this baseline should be an in-house repair facility, assuming complete availability of technical information. This part of the analysis would necessarily focus on issues of scheduling and priorities, deciding what sort of diagnosis and repair or replacement operations should be performed at the various levels of operation, and how materiel returned to the depot should be dealt with. In particular, the analysis should prescribe a level and a configuration of excess testing and repair capacity that best meets anticipated surge and sustainability goals under foreseeable combat conditions. At this level, cost factors must be introduced to reconcile the "lean and mean" goals of peacetime efficiency with the ability to respond rapidly to a variety of possible contingencies.

The second task is to introduce the costs associated with information transfer and to project the effect on weapons design of an entirely organic facility. This departs from the "best-case" analysis above in that it includes compromises on the level of technical expertise and the reliability of systems stemming from the presence of in-house repair facilities. It would serve as the standard of comparison for alternative contractual arrangements.

The third task is to model various contractor-operated options. These would vary according to the ownership, location, and flexibility of test equipment and provisions to secure adequate performance, but would assume honest performance by contractors. The fourth and fifth tasks would introduce strategic and collusive behavior, respectively, to obtain realistic estimates of the costs and flexibilities of various alternative arrangements. There is a substantial degree of overlap between the latter three tasks, which are divided for conceptual clarity. Important considerations would include monitoring costs, information costs, and fixed-capital transferability, as well as dynamic considerations.

Appendix F

BUSINESS STRATEGY AND SOURCES OF REPAIR

Considerable research has been undertaken to formalize the concept of corporate strategy and to understand its implications for business definition, organization structure, and functional strategies. A number of important books document the results of this research effort (e.g., Andrews (1980), Porter (1980), and Hayes and Wheelwright (1984)). Although it addresses production rather than repair decisions, Porter's book encapsulates an analytic framework that is relevant to the source-selection problem. Particularly relevant sections of the book address: (1) purchasing strategy issues; (2) sources of supplier power; (3) strategies to negate supplier power; and (4) the rationale for vertical integration. The book's key points in each of these areas, along with a commentary concerning their application to the repair-source-selection problem, are summarized below.

With regard to purchasing strategy, Porter identifies the key issues as:

- The stability and competitiveness of the supplier pool;
- The means used for:
  - Allocation of purchases;
  - Creating leverage with suppliers;
- Determining the optimal degree of vertical integration.

Unfortunately, particularly for the low volume items, there is no "pool" of suppliers for component repair. Even for components with high repair volume, the range of potential suppliers is limited for the reasons outlined above. These factors limit the government's ability to create leverage with suppliers, because suppliers tend to have the preponderance of "power" in the relationship.

Porter identifies the structural sources of such power as:

- Concentration in the industry;
- A lack of dependence on the customer;
- Costs that the customer would incur for:
    - Obtaining information needed to "shop" for and negotiate with alternative suppliers;
    - "Switching" suppliers;
- A unique product, for which there are few alternative sources.

This description of the factors that promote supplier power corresponds closely with the characteristics of commercial "suppliers" of component repair capability, particularly for high-technology repairs. The industry is not only concentrated, there is usually only one source for any particular component. Although the government may be the only customer for repair services, repair is neither the biggest nor the most profitable part of the business for most such sources.

Most of the strategies Porter proposes for negating supplier power are infeasible in the aviation component repair business. His proposed list of strategies includes:

- Spreading purchases and qualifying alternative sources;
- Promoting standardization;
- Avoiding switching costs;
- Threatening backward integration;
- Use of "tapered integration," where production is split between in-house sources and contract.

The military is limited in its ability to spread purchases because of low repair volumes or the unique expertise of its suppliers. Although standardization would result in an increase in the average component demand rate, maintenance managers have little control over the configuration of the weapons they are charged with supporting. Switching costs are not easily avoided, because the military *is* dependent on its current source of supply and often lacks the information needed to search out alternative suppliers.

This leaves two variants of vertical integration. Porter discusses several common rationales for such integration, again in a production rather than a repair context. An organization may choose to vertically integrate its production process to:

- Achieve economies;
- Tap into technology;
- Assure a supply of critical materials;
- Offset the bargaining power of external suppliers so as to avoid input cost distortions.

Hayes and Wheelwright summarize the major arguments that have been advanced for vertical integration as follows:

- Information sharing and the reduction of production uncertainties;
- Reductions in "transaction costs;"
- Increasing "market power."

The third rationale for vertical integration should not apply to the repair sourcing problem. The "market" consists of operational force demands, and the objective of the logistics system is to support rather than to control its customers, although some commercial suppliers do have market power by virtue of their unique technical knowledge. The other two are relevant repair-source-selection considerations.

It was noted earlier that an effective information system is needed to control a maintenance facility and take advantage of the flexibility provided by scope of repair.[1] Just as it is easier to control the flow of material to and from a few rather than many repair locations, it is easier to control the flow of information concerning item criticality when the number of repair points is limited. This communication advantage results because communication takes place through channels

[1]A contractor that repairs more than one item has some scope of repair, albeit considerably less than a facility designed to repair a wide range of items.

Appendix G

SUMMARY OF COST AND RELATED FACTORS
IN AIRCRAFT MAINTENANCE

Lucian J. Hunt, Vice President, American Airlines
(General Management Systems, 1982)

1. Diversified and integrated facilities, commercial or military,
    whose sole mission is overhaul and repair of aircraft, engines
    and components, have demonstrated their capability to produce
    higher quality and more reliable products than other sources of
    limited capability. These other sources include the product
    manufacturer and the specialized overhaul facilities limited to
    a few products or a single workload category.

2. An integrated plant with the broad capability to perform
    workload categories of airframes, engines, and components on a
    self-sufficient basis is exposed to a higher fixed overhead,
    and, to a lesser extent, a higher variable overhead. Overhaul
    sources of limited capability will have substantially less
    overhead than the integrated, highly diversified plant. Their
    over-all capability, depths of rework, and levels of quality
    produced are also influenced by such lower overhead support.

3. The proportionate costs of labor and material vary by workload
    category, airframes, engines and components. Except for the
    airframe workload category, material costs transcend
    expenditures for direct labor. Considering the predominance of
    workload in the engine and component workload categories, an
    integrated facility can exercise important cost options between
    the relative expenditures for labor and material in overhaul of
    any product. A limited or specialized facility without the
    full capability to "repair vs. replace", and one who has little
    or no incentive to control costs of carrying inventory or
    material consumption, will not generally exercise the desired
    cost option toward achieving minimum cost of product
    overhauled.

4. The cost of carrying inventory is a vital factor in determining
whether to resort to multiple sourcing or to use a single
integrated facility of broad capability. Multiple sources may
impose inventory pipelines which can double or even triple the
amount of inventory investment. Assuming such investment is
for mobilization purposes, excessive pipelines may not be too
vital an economic factor. However, if such inventories are not
essential to mobilization requirements, then the additional
annual carrying costs for excess inventory will conservatively
amount to as much as 15 percent of the value of such excess
inventory.

5. Quality of product is the most important single objective in
overhaul and repair of aeronautical equipment. Quality
performance of the product in service, or the lack of it,
influences the ultimate cost to a greater degree than direct
labor, material, or overhead costs of producing the product.
Product quality directly influences the yield of the product in
hours between overhauls and the amortization of overhaul costs
over hours yielded in service. The ultimate measure of quality
is three-fold: (1) military readiness, (2) influence upon field
operating and maintenance costs, and (3) the cost per product
hour yield based upon amortized overhaul cost.

6. For complex workload declared to be militarily essential, the
flexibility of control is vital not only to operational
readiness, but to the economics of support logistics. When
multiple overhaul sources are used for total support,
management options between recurring expenses and capital
investment are difficult to recognize and to control.
Recurring expenses include direct labor and material, plus
overhead charges for overhaul work. Capital investment
includes material inventories of aircraft, engines, and all
related rotables and spare parts, plus plant capital investment
in tooling, equipment and facilities.

7. Airline overhaul depots, which are similar to Navy O&R Departments, are able to assure maximum quality of product and minimum cost per operating hour yielded by that product. Further, the flexibility of control which airlines can exercise through their diversified and integrated overhaul depots permits complete exercise of choosing the proper cost option between recurring expense and capital investment.

8. A technical specification is not a positive means either of controlling product quality or compliance as to depths of rework as they influence labor and material expenses. Therefore, specifications are merely guidelines and as such do not permit a contracting officer to exercise appropriate cost options during the course of a contractor's performance in providing overhaul services.

9. Defense policy and procedures used for source selection or contract letting are not always pertinent to the means available for follow-up contract administration. If a contractor fails to provide acceptable quality services for the agreed price, there is in fact little discipline which can be brought to bear by the government. Intangibles are too great to prove conclusively that a contractor failed to produce what the government contracted for in quality and price. In some cases reliability or yield data which may historically reflect poor quality cannot be reconciled to the source that produced the product.

10. An integrated overhaul plant with a demonstrated reputation for quality workmanship requires minimum contract surveillance. Sources of limited capabilities require greater and often continuous surveillance to assure the government gets what is contracted for and must have for logistic support of operating forces. In the absence of such surveillance, the government may be exposed to inordinate maintenance costs without the benefit of receiving quality materials, subsequent performance and yield of product.

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11. Unquestionably, the military departments will continue to farm out aircraft, engine and component workloads of non-essential character. In so doing, it is still important that the military achieve highest product quality at minimum cost to the government. This minimum cost must include the total cost to the government, i.e. give full weight to the influence of product quality to readiness and hours yielded, as well as the cost influence of all government furnished material and inventories required to deliver the product to service.

12. Positive and self-disciplining contracting policies and methods must be developed for commercial overhaul programs. These procedures should inject the factors of *quality* and *total material cost* to overhaul a product. To do this requires rigorous screening and selecting of commercial sources who have a demonstrated integrity for producing quality at minimum cost. Consideration should be given to extending the duration of overhaul contracts from one year, with renewable option for one or two more, to a term of three or more years. This extended period would permit a commercial source to invest capital in improved equipment, train skills to produce quality and retain them long enough to achieve favorable learning curves. Warranty provisions should also be applied to assure optimum product quality and yield. The above contracting procedures are used by major airlines and are generally used for military R&D and certain new procurement programs. Equally stringent consideration should be given in contracting for military maintenance and overhaul support. Incentive and penalty provisions also should be used in those contracts which have definitive requirements for measuring the resulting product quality, yield and total cost to the government.

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